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AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

Lyndon B. Johnson Space Center
Houston, Texas

August 15-16, 1990

Sponsored by

NASA Office of Space Flight

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Volume I

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS

PREFACE

This document consists of the presentations submitted at the Autonomous Rendezvous and Docking (ARD) Conference. The document contains three volumes:

VOLUME I	ARD Hardware Technology
VOLUME II	ARD Software Technology
VOLUME III	ARD Operations

Information contained herein should not be construed as being the official NASA position. Responsibility for content and technical accuracy lies with each respective author.

The ARD Conference was sponsored by NASA Office of Space Flight, NASA Office of Aeronautics, Exploration and Technology, and NASA Space Servicing Systems Project Office.

James S. Moore
James S. Moore
Manager of NASA Space Servicing Systems Project Office
NASA-JSC
Code IA 141

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August 15-16, 1990

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Session III ARD Operations	Don J. Pearson NASA-Johnson Space Center
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INTRODUCTION

Autonomous Rendezvous and Docking (ARD) will be a requirement for future space programs. Clear examples include satellite servicing, repair, recovery, and reboost in the near term, and the longer range lunar and planetary exploration programs. Indeed, ARD will permit more aggressive unmanned space activities, while providing a valuable operational capability for manned missions. The purpose of this Conference is to identify the technologies required for an on-orbit demonstration of ARD, assess the maturity of those technologies, and provide the necessary insight for a quality assessment of programmatic management, technical, schedule, and cost risks.

James S. Moore
ARD Conference Chairman

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Dr. Neville Marzwell
NASA-Johnson Space Center
Technical Session Chairman

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

SUMMARY OF SESSION I

AR& D HARDWARE TECHNOLOGY

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AR&D HARDWARE TECHNOLOGY

SENSORY CAPABILITIES

HAVE ... STATE OF THE ART	HAVE NOT ... TECHNOLOGY ADVANCEMENT
- SENSORY CAPABILITIES EXIST FOR GUIDANCE, TRACKING, FEATURES DETECTION AND RECOGNITION AND PROCESSING THAT CAN OPERATE UNDER SPACE ENVIRONMENT. E.G., FLIGHT QUALIFIED HARDWARE SUCH AS ASTROS, ETC. - MOST SENSORY TECHNOLOGIES SEEM TO BE ADDRESSED IN EUROPE AND THE USA	- MINIMIZATION OF # OF TARGET AND ILLUMINATION PATTTERNS TO REDUCE OPERATION CONSTRAINTS. - INTEGRATION OF SENSORY TECHNOLOGY INTO A COMPLIANT ROBUST TRACKING AND DOCKING SYSTEM. - COMPUTER IMAGE PROCESSING TO MIMIC BRAIN PERCEPTION AND REAL TIME RESPONSE. - ADVANCED SENSORS CAPABLE TO MEASURE GEOMETRY AND DYNAMICS DIRECTLY. - REQUIRED MAXIMUM SENSORY ACCURACY FOR SPECIFIC MISSION ENVELOPES. - SENSORY FUSION ARCHITECTURE - LOW COST, HIGH RELIABILITY COMPONENTS. - RANGE RATE SENSORS 10-15 METER/SEC. - OPTIMIZATION OF INTEGRATED SENSORY SYSTEM AND PACKAGING..

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AR&D HARDWARE TECHNOLOGY

MECHANISM CAPABILITIES

HAVE ... STATE OF THE ART	HAVE NOT ... TECHNOLOGY ADVANCEMENT
- DOCKING/BERTHING SYSTEM CONCEPTS AND ENGINEERING MODELS EXIST THAT ARE SUPPORTED BY COMPUTER MODELS AND SIMULATIONS.	- EVALUATION OF DOCKING MECHANISM DESIGNS AND DOCKING MECHANISM SYSTEMS AND PERFORMANCE TRADES IN TERMS OF MISSION ENVELOPES KEY PARAMETERS. - ON-ORBIT VERIFICATION INTEGRATING ALL ELEMENTS (S/W & H/W) TO ASSESS PLANNED AND EXISTING MECHANISM PERFORMANCE TRADES. - MINIMUM TOLERANCE REQUIREMENTS FOR SPECIFIC MISSION ENVELOPES.

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AR&D HARDWARE TECHNOLOGY

SYSTEM CAPABILITIES

HAVE ... STATE OF THE ART	HAVE NOT ... TECHNOLOGY ADVANCEMENT
- GROUND HARDWARE TEST, SIMULATION AND EVALUATION FACILITIES.	- REALISTIC ON-ORBIT SYSTEM END TO END SYSTEM PERFORMANCE VALIDATION (S/W & H/W) - MAN IN THE LOOP (SUPERVISING VS. MANNED CONTROL). • GROUND CONTROL STATION • LEVEL OF AUTONOMY/SHARED-TRADED CONTROL • COMPUTER ALGORITHM FOR REAL TIME OPERATION - STRUCTURE/DYNAMICS/CONTROL INTERACTIONS - MULTI-VEHICLE GN&C INTERACTIONS. - RIGOROUS SYSTEM ENGINEERING DESIGNS WHICH CONSIDER COST, MASS, FUEL, MANEUVERABILITY SOFT/HARD DOCK & RELIABILITY - RIGOROUS SYSTEM FOR ADDRESSING REDUNDANCY (MULTIPLE SENSORY INPUTS) AND FAULT TOLERANCE (GUIDANCE, NAVIGATION AND COTNROL)

AR&D HARDWARE TECHNOLOGY

SUMMARY CAPABILITIES

HAVE ... STATE OF THE ART	HAVE NOT ... TECHNOLOGY ADVANCEMENT
- VIABLE CONCEPTS (SENSORS, SUBSYSTEMS, MECHANISMS) AND PROTOTYPES EXIST I.E., AR&D IS TECHNOLOGICALLY FEASIBLE TODAY ... NO NEW TECHNOLOGY IS NEEDED	- INTEGRATED FLIGHT SYSTEMS. - OPTIMIZED DESIGN AND PACKAGING OF SYSTEMS AND SUBSYSTEMS - A SINGLE SENSOR CAPABLE OF COVERING FROM MEDIUM RANGE TO PROXIMITY (NEAR CONTACT) OPERATIONS. - A RELIABLE MECHANISM FOR AUTONOMOUS SPACECRAFT DOCKING.

ARD HARDWARE TECHNOLOGY

ABSTRACTS

Docking Mechanisms: Some European Development Programs

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MATRA, Toulouse, France

One of the foreseen missions of the HERMES space vehicle is the servicing of the COLUMBUS FREE FLYER (CFF). Docking between the two spacecraft is a critical operation. A major item involved in rendezvous and docking operations is the docking mechanism.

The docking mechanism is required to perform the following functions: positioning and reception during docking operations; centering and capture; residual energy dissipation, structural and functional connections (between both spacecraft); and passage pressurization.

In support of the European Space Agency's (ESA's) Rendezvous and Docking Pre-Development Program, SENER is developing and building a model docking mechanism.

The performance of different docking systems will be evaluated by testing different configurations of the docking system model on both the Docking Dynamics Test Facility (DDTF) and computer simulations.

The Docking Mechanism Model, which is composed of both passive and active halves, incorporates those assemblies that are involved in the docking process, viz., guiding devices, capture latches, and attenuation systems. Tuning of features of these assemblies will allow the analysis of different parameters and functions:

- Guiding - shape, slope, location, and quantity
- Attenuation - stiffness and damping characteristics
- Capture - capture strategies, capture velocities, location, quantity and capture range of the latches.

Another key function of the Docking Mechanism is the sealing of interfaces between both Docking Mechanism halves. SENER is currently conducting a development program on sealing to determine the performance of sealing systems in terms of: characteristics of seals (materials, shapes, etc.), leakage (rates, on-orbit detection and verification methods), impact of environmental conditions on sealing, structural latching characteristics (quantity, failure tolerance, latching force, etc.).

The presentation describes the status of these programs and includes a summary description of other rendezvous and docking activities (control systems, sensors, man-in-the-loop simulations, etc.) that are being performed in ESA's Pre-Development Program.

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Optical Position Sensor Development at JPL

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The proposed GLAM-VISTA (Global Land/Ice Altimeter Mission-Vertical Interferometric SAR Tethered Altimeter) mission involves two satellites having a fixed orientation to each other. A novel angular position sensor based on a lateral cell was designed to complement a conventional laser range finder to measure the relative positions of antennas mounted on the satellites. Although conceived as a station-keeping sensor, the design has applications for rendezvous and docking. The presentation includes a description of the GLAM-VISTA instrument and briefly describes some of the background material relative to the sensor development at JPL. This will include an update on SHAPES (Spatial, High-Accuracy, Position-Encoding Sensor), a position sensor capable of simultaneous 3-dimensional position measurements of multiple targets with sub-millimeter accuracy at a 10-Hertz update rate.

Docking Mechanism Design: Analysis of Front-End Requirements & Verification Tools

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DR. W. Fehse, A. Tobias
EUROPEAN SPACE AGENCY, Noordwijk, The Netherlands
J. J. Gonzales-Vallejo
SENER, Las Arenas, Spain

Activities performed under ESA's Rendezvous and Docking Proof-of-Concept program and the related software and hardware tools are presented and described.

A half-scale docking mechanism mockup is being developed by Matra. The mockup consists of a guiding stage (composed of petals), a passive attenuation stage (composed of six springs and dampers), and capture latches. The characteristics of the guiding petals (orientation, inclination, shape) and most of the attenuation stage (springs, stiffness, damping factor) are tunable for investigation during tests to be performed on the Docking Dynamics Test Facility (DDTF) at Matra. Using force transducers, this facility permits the computation of forces and torques applied to the chaser and target vehicles, and then applies the correct kinematics to screwjacks moving one-half of the docking mechanism.

A software tool, the Docking Simulation Program (DSP), is used in parallel for cross-correlation with hardware test results.

The description of the DDTF and its performance is presented. The capabilities of the DSP are described.

Comparisons are made between rendezvous control system requirements and docking/berthing mechanism test results.

Overview of CNES Rendezvous and Docking Activities

M. Le Du
CNES - (French National Space Agency)
Centre Spatial del Toulouse
France

Rendezvous and docking techniques and technologies represent a major step in the development of the HERMES program. A significant amount of work has been performed in Europe to define rendezvous concepts, to design rendezvous systems and equipment, and to provide rendezvous verification tools. Rendezvous sensors based on CCD imaging and laser telemetry technologies have been developed and tested at breadboard levels in realistic dynamic conditions. A scaled docking mechanism has been manufactured and will be tested by the end of the year on a dedicated dynamic 6-DOF motion simulator. A large program of studies is also going on which will identify and optimize all the operation and target interface requirements involved in different rendezvous scenarios.

Studies are performed to optimize the different rendezvous mission phases: phasing, homing, final approach and retreat. These studies take into account the ous failure potentialities.

Dedicated simulators are available:

- to assess the relative dynamics of vehicles, to validate strategies, automatic control laws, and to test manual capabilities of the human operator, in relation with a realtime 3-D graphics animation, and
- to analyze the need and performances of expert system techniques used to help the pilot for failure diagnosis and operation replanning.

A Docking Dynamics Test Facility to verify docking hardware has been set up by CNES. The facility reproduces the final approach of the rendezvous and the docking interactions. It is used to test sensors, mechanisms, and "man-in-the-loop" performances during the proximity operations and docking. In parallel, the European Space Agency (ESA) is developing the European Proximity Operation Simulator to represent the closing phase of the rendezvous. It will be used to test rendezvous sensors and algorithms and the man-in-the-loop concepts.

Video-Based Sensor for Autonomous Docking

Richard T. Howard
NASA - Marshall Space Flight Center
Huntsville, Alabama 35812

A sensor has been developed at the NASA Marshall Spaceflight Center (MSFC) that allows the performance of automated docking between two vehicles. The sensor consists of a charge-coupled device (CCD) camera, two sets of laser diodes, a realtime video frame grabber, and an 80386-based computer. The baseline target is a modified RMS grapple fixture target that has retro-reflective tape covered by narrow bandpass optical filters at each end and on the center post.

The sensor illuminates the target with each set of laser diodes and digitizes a picture each time, then subtracts the second picture from the first to obtain a low-noise image. From the target's image on the screen, the relative positions and attitudes of the sensor to the target can be calculated, and thins information can be fed into a guidance algorithm.

The current breadboard setup has a range of 40 feet using the modified RMS target and a range of 150 feet using a larger target with corner-cube reflectors instead of tape. It has been used for large-scale closed-loop automatic docking in three-dregrees-of-freedom (DOF) and berthing in six-degrees-of-freedom in the Flights Robotic Laboratory at MSFC.

Description and Performances of the MATRA CCD Camera Sensor

Christian Pauvert, T. Bomer
MATRA ESPACE, Toulouse, France

Matra activity on the RV sensor based on the CCD camera technology is presented. At present, a functionally representative breadboard has been developed and will be tested on the European Proximity Operation System beginning next year.

During image acquisition, a laser pulse is generated and the reflected light provided by the retro-reflectors of the target is collected on a photo sensitive area. The detection is performed by a CCD array detector, sequenced with a specific mode which minimi stray light influences, allowing very good rejection of unwanted optical signals. The sensor can be used in imager mode (between 200m and 0.5m) providing distance, LOS and relative attitude between chaser and the target vehicle to be determined by the number of echoes. It can also be used in LIDAR mode (between 1Km and 200m).

A general description of the hardware, including an optical head (composed of a lens and an optical filter, the CCD detector, its cooler, the proximity electronics, and the optical interface for the laser emission) and the electronics unit (mainly composed of sequencing logics, a video signal processing channel, a processor, and a lighting unit connected to the optical head). Functional performances of the sensor system will be presented.

Laser Docking Sensor

Joseph L. Prather
NASA Johnson Space Center
Houston, Texas 77058

A Laser (Rendezvous) and Docking Sensor, LDS, is being developed to demonstrate, on-orbit, the technology necessary for aiding future spacecraft in station keeping, docking, and berthing with possible target vehicles. Funded by the NASA Office of Space Flight, the candidate optical sensor will also enable automated docking by more accurately determining relative spacecraft position and rates between docking vehicles. The LDS is being developed by the McDonnell Douglas Space Systems Company for the NASA Johnson Space Center and is being projected for use in the Satellite Servicer System Flight Demonstration currently scheduled for 1996.

The presentation will briefly discuss the LDS performance requirements and summarize some of the potential implementation techniques.

Hybrid (Optical and Digital) Image Processing for Vision-Based Control

Richard D. Juday
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NASA Johnson Space Center
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Hybrid vision is the result of image processing that is partly digital, partly optical. The Johnson Space Center program is discussed. Its main elements are spatial light modulators, video rate image coordinate transformations, Fourier optics filter optimization for signal-to-noise ratio, and synthetic estimation filters.

Autonomous Rendezvous and Docking System Design and Simulations

Richard W. Dabney
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Huntsville, Alabama

A complete, short-range, autonomous rendezvous and docking system has been designed and evaluated under realistic full-scale conditions using an airbearing vehicle at the NASA Marshall Space Flight Center (MSFC) Flat-Floor facility. The system uses a CCD-based sensor which tracks the location of three retro-reflectors attached to a target spacecraft. An inverse-perspective algorithm is then used to determine relative position and attitude from these centroid coordinates. Both traditional and neural-network based techniques have been used for this function. After filtering to reduce noise levels, the relative state data are input to a set of six independent proportional-derivative phase plane controllers, which generate thruster firing commands to the air-bearing vehicle.

A large number of runs have been made since the first successful demonstration in December, 1988, and a success rate of approximately 99% has been achieved. Recent improvements to the system include docking with targets covered with multi-layer reflective insulation in the presence of ambient light, despite the unwanted reflections that result.

The presentation also includes plans for future work, including neural network control algorithms and full-scale demonstration of tumbling target docking.

ARD HARDWARE TECHNOLOGY

PRESENTATIONS

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DOCKING MECHANISMS: SOME EUROPEAN DEVELOPMENT PROGRAMMES
(INVESTIGATIONS ON DOCKING SYSTEMS FOR EUROPEAN SPACECRAFT)

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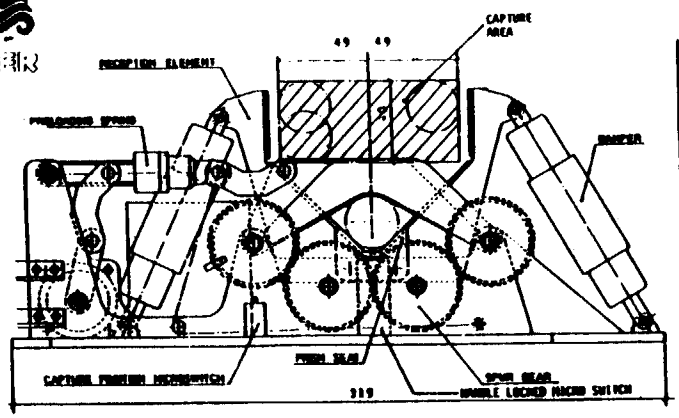
1. INTRODUCTION

DOCKING/BERTHING SYSTEMS FOR UNPRESSURISED AND PRESSURISED CONNECTIONS HAVE BEEN INVESTIGATED IN EUROPE IN THE LASTS TEN YEARS.

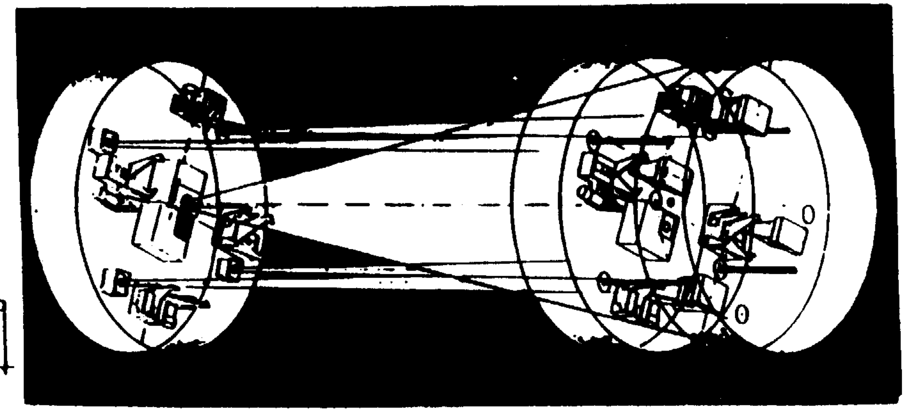
INITIAL TECHNOLOGY INVESTIGATIONS PAVED THE WAY FOR THE USER PROJECTS **HERMES** AND **COLUMBUS** THAT REQUIRE PRESSURISED PASSAGES.

TECHNOLOGY INVESTIGATIONS HAVE CONTINUED IN PARALLEL AND AHEAD OF THE USER PROJECTS. THIS IS REQUIRED FOR EARLY IDENTIFICATION AND SOLUTION OF KEY ISSUES AND ALSO TO PREPARE THE APPROPRIATE TOOLS FOR DEVELOPMENT AND VERIFICATION.

THE EARLY TECHNOLOGY ACTIVITIES, THE BASELINE CONCEPTS OF THE **HERMES AND COLUMBUS** PROJECTS AND THE CURRENT TECHNOLOGY PROGRAMMES AIMED TO PROVIDE EARLY PROOF OF THOSE CONCEPTS ARE PRESENTED.



Latching Mechanism Design



2. BACKGROUND

2.1 DOCKING SYSTEMS FOR UNPRESSURISED CONNECTION

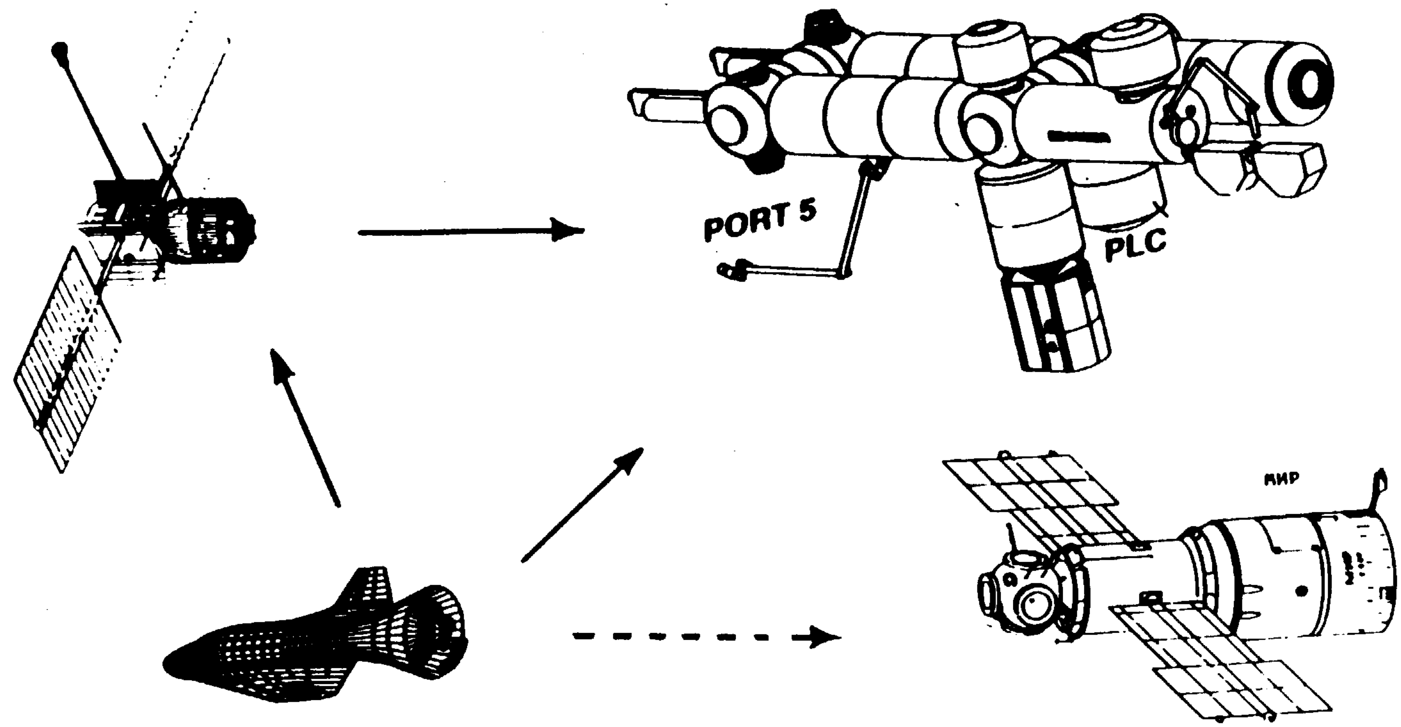
* DOCKING SYSTEMS FOR UNPRESSURISED CONNECTION WERE INVESTIGATED SINCE BEGINNING OF EIGHTIES FOR THE ASSEMBLY OF LARGE PLATFORMS IN ORBIT.

* ACCURATE, SOFT AOCS CONTROLLED DOCKING PROCESS WAS PREFERRED. MISALIGNMENTS OF 10 mm AND 1 deg, AND RESIDUAL RATES OF 10 mm/s (APPROACH), 3 mm/s (LAT.) AND 0.05 deg/s (ANGULAR).

* BASELINE SYSTEM: ACTIVE HALF ON CHASER AND PASSIVE HALF ON TARGET
  - GUIDANCE FUNCTION: V GUIDES ON CHASER, MATCHING BARS ON TARGET.
  - ATTENUATION: PASSIVE ATTENUATION ON V GUIDES AND LATCH CLAWS.
  - CAPTURE/CLOSURE: 4 DOUBLE CLAW LATCHES ON CHASER SIDE (1 REDUNDANT).
  - STRUCTURAL MATING: PROVIDED BY CAPTURE LATCHES.
  - UTILITY CONNECTION: AUTOMATIC ELECTRIC AND FLUID CONNECTION SYSTEMS.
  - CONTROL ELECTRONICS: AUTONOMOUS UNDER OVERALL AUTHORITY OF GNC SYSTEM.

* BREADBOARD WAS BUILT AND TESTED ON AIR BEARING DOCKING FACILITY. DYNAMICS WAS ALSO ANALYSED BY MEANS OF SOFTWARE SIMULATION TOOL.

* CONCEPT CURRENTLY BEING RECONSIDERED FOR USE IN LOGISTICS VEHICLES.



2.2 THE FIRST EUROPEAN DOCKING/BERTHING SCENARIOS

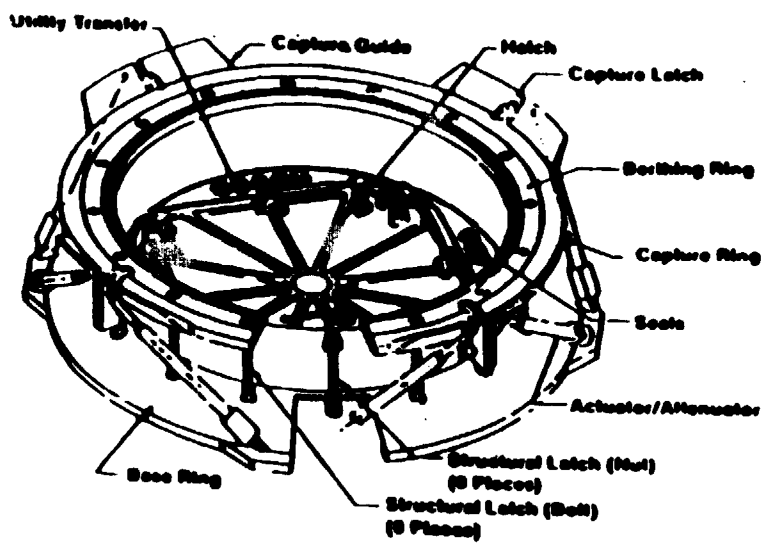
* FIRST EUROPEAN DOCKING SCENARIOS WILL INVOLVE MANNED OR MAN TENDED SPACECRAFT AS THE COLUMBUS FREE FLYER AND THE HERMES SPACE VEHICLE.

* THE COLUMBUS ATTACHED LABORATORY IS PERMANENTLY IN ORBIT AS AN ELEMENT OF THE SPACE STATION FREEDOM.

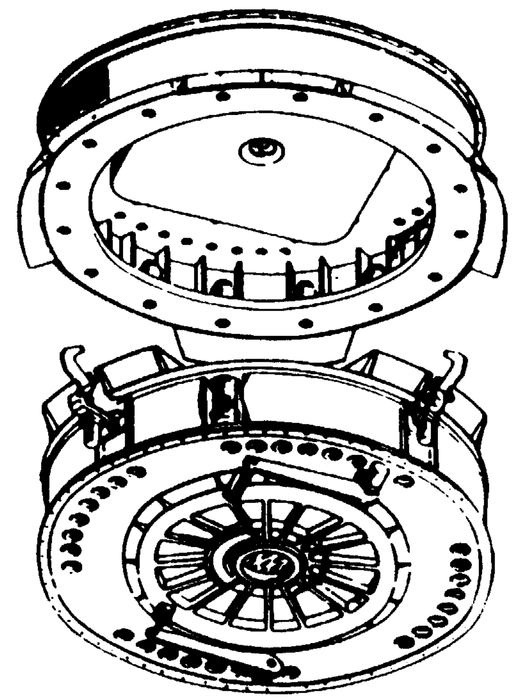
* THE COLUMBUS FREE FLYER LABORATORY IS PERMANENTLY IN ORBIT AND VISITS THE SPACE STATION FREEDOM FOR SERVICING EVERY 3 - 4 YEARS.

* HERMES MAIN MISSION IS THE SERVICING OF THE COLUMBUS FREE FLYER EVERY SIX MONTHS. THE VISIT OF THE SPACE STATION MISSION IS ALSO A DESIGN MISSION OF THE HERMES. HERMES MAY ALSO VISIT THE SOVIET SPACE STATION MIR.

FREEDOM DESIGN UNTIL 1989



COMPATIBLE TO MEET FREEDOM DESIGN



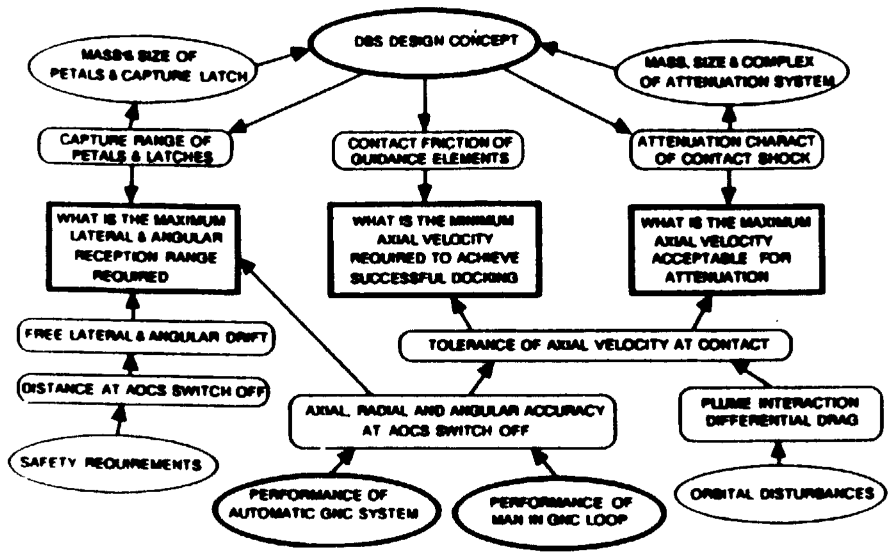
3. DOCKING/BERTHING SYSTEMS (DBS) FOR HERMES AND COLUMBUS FREE FLYER

* DRIVEN BY COMPATIBILITY WITH SPACE STATION FREEDOM.

* STATUS 1989:
- COLUMBUS FREE FLYER: PASSIVE HALF, NO CAPTURE LATCHES, NO ACTIVE STRUCTURAL LATCHES, NO DEDICATED ATTENUATION SYSTEMS, NO SEALS AT MATING INTERFACE.
- HERMES: MISSION CONFIGURABLE OUTFITTING BASIC MODULE WITH PROVISIONS FOR:
  - DOCKING TO COLUMBUS FREE FLYER: CAPTURE AND STRUCTURAL LATCHES, ATTENUATION, SEALS.
  - BERTHING TO SPACE STATION FREEDOM: CONTINGENCY SEPARATION DRIVES (ACTIVE LATCHES,...)

* STATUS 1990: WORK IN PROGRESS CONSIDERING EVOLUTION IN SPACE STATION SCENARIO.

DESIGN COMPATIBILITY OF GNC AND DOCKING/BERTHING SYSTEMS



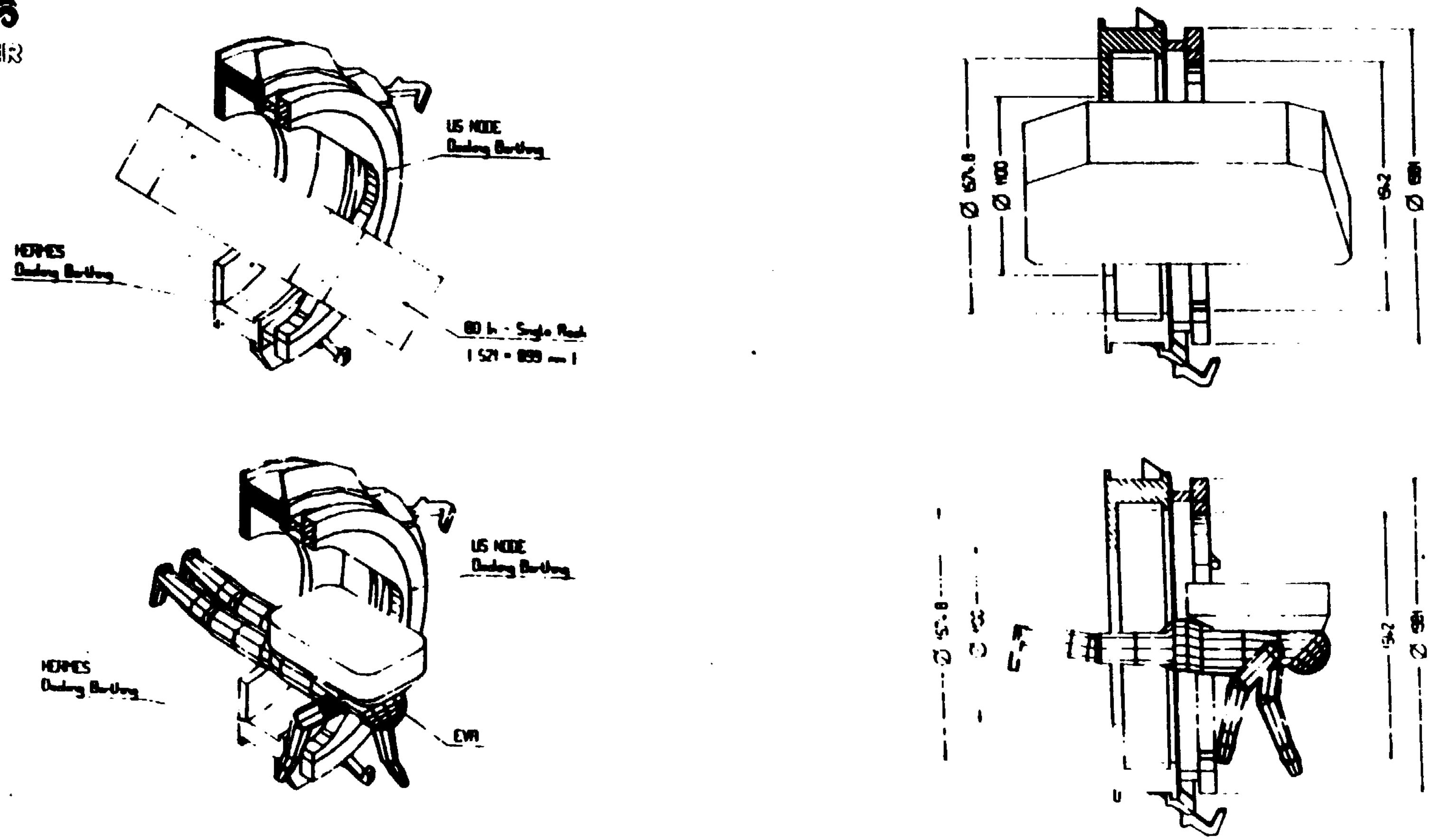
CONTACT CONDITIONS	FREEDOM BERTHING	HERMES DOCKING (TBC)
AXIAL VELOCITY VX (M/S)	0.046	0.03
LATERAL VELOCITY VZ (M/S)	0.046	0.02
LAT. MISALIGNMENT (M)	0.077	0.05
ANGULAR RATE		
(O/S) ROLL	0.52	0.2
(O/S) YAW/PITCH	0.2	0.2
ANGULAR ERROR		
(DEG) ROLL	1.5	1.5
(DEG) YAW/PITCH	1.5	1.5

FRONT-END FUNCTIONS (CAPTURE, GUIDANCE, ATTENUATION, CLOSURE) ARE DRIVEN BY INERTIA PROPERTIES OF THE SPACECRAFT AND THE CONTACT CONDITIONS (APPROACH VELOCITIES AND MISALIGNMENTS):

* IF RESIDUAL MISALIGNMENTS ARE SMALL:
  - DOCKING FRONT-END ELEMENTS (GUIDING PETALS, CAPTURE LATCHES) CAN BE SMALLER AND LIGHTER, BUT
  - CHASER GNC MUST BE ACCURATE, RV SENSOR BIAS MUST BE SMALL, TARGET WAITING CONDITIONS ARE DEMANDING.

* IF RESIDUAL RATES ARE SMALL:
  - ATTENUATION REQUIREMENTS ON DBS ARE LOW AND PASSIVE ATTENUATION SYSTEMS CAN BE USED: NEED FOR DEDICATED DEPLOYMENT/CLOSURE DEVICES CAN BE AVOIDED, BUT
  - REQUIREMENTS ON GNC SYSTEM INCREASE, E.G. SENSOR NOISE AND GNC BANDWIDTH MUST BE LOWER, TARGET WAITING CONDITIONS ARE MORE DEMANDING.

* PREFERENCE IS FOR ACCURACY, LOW IMPACT DOCKING.



TRANSFER REQUIREMENTS:

* **PRESSURISED PASSAGE** DEFINES SIZE OF DBS. IN HERMES - COLUMBUS SCENARIO REQUIREMENTS ARE: ASTRONAUT IN EVA SUIT, SINGLE RACK.

* **UTILITIES** (EXCEPT HAZARDOUS) SHALL BE ROUTED AND CONNECTED INSIDE PRESSURISED VOLUME WITHOUT OBSTRUCTING PASSAGEWAY. MANUAL CONNECTION BY JUMPERS.

SENER

HERMES DOCKING SYSTEM

* HERMES DOCKING SYSTEM IS THE DOCKING MECHANISM ACTIVE HALF WHEN HERMES DOCKS TO COLUMBUS FREE FLYER. MAIN FUNCTIONS: RECEPTION AND POSITIONING DURING DOCKING PROCESS, CAPTURE OF THE TARGET SPACECRAFT, RESIDUAL ENERGY DISSIPATION, STRUCTURAL AND FUNCTIONAL CONNECTION BETWEEN BOTH SPACE VEHICLES, PASSAGE PRESSURISATION.

* HERMES DOCKING SYSTEM CHARACTERISTICS DRIVEN BY: RELATIVE APPROACH CONDITIONS, MASS PROPERTIES OF BOTH SPACECRAFT AND COLUMBUS FREE FLYER DOCKING/BERTHING MECHANISM (PASSIVE HALF) CHARACTERISTICS (CFF D/BM SHALL BE SIMULTANEOUSLY COMPATIBLE WITH HERMES AND SPACE STATION FREEDOM PORTS).

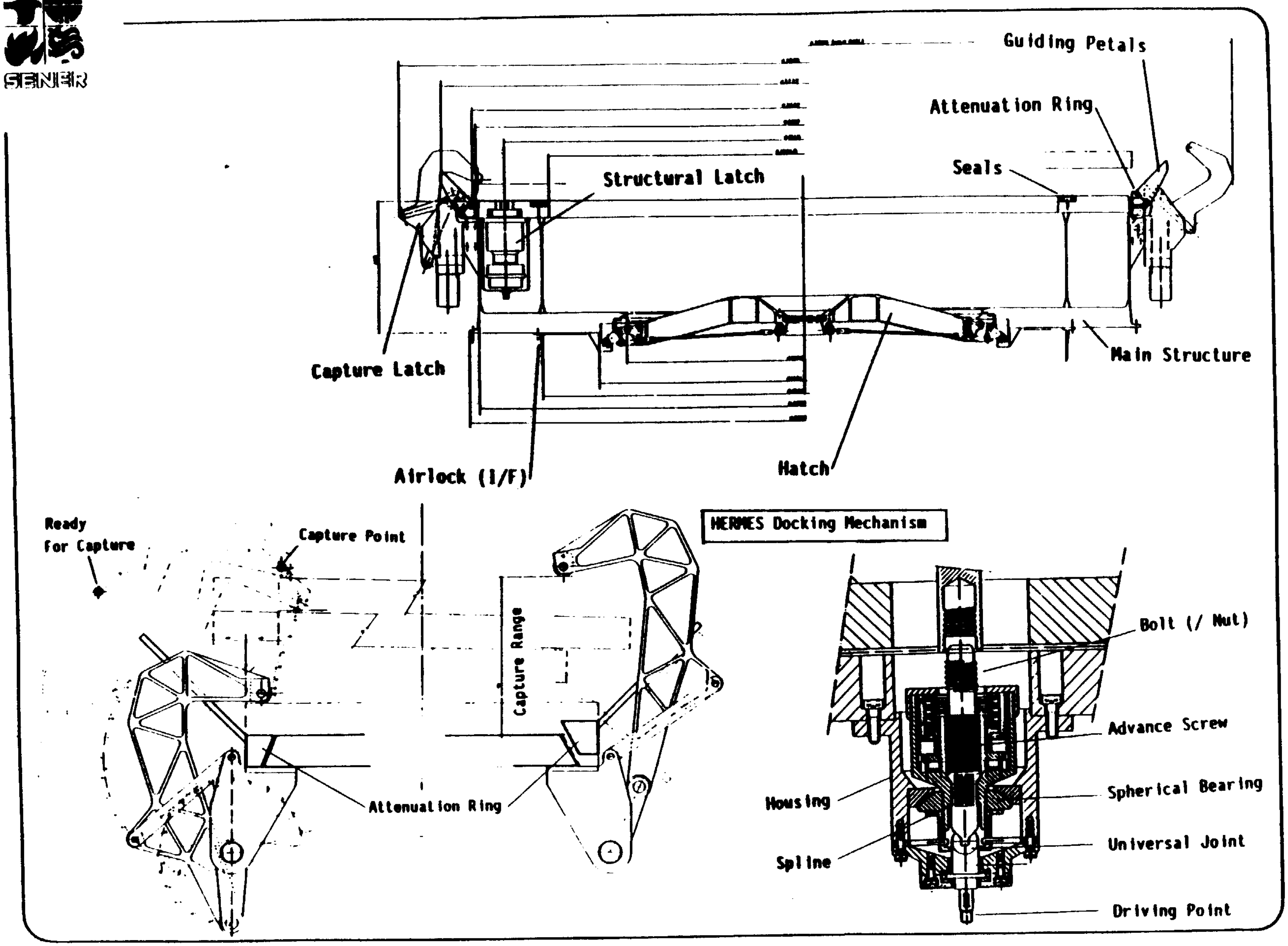
* MAIN CHARACTERISTICS:

  - **GUIDING SYSTEM** CONSISTING OF FOUR GUIDING PETALS EXTERNALLY LOCATED AND MOUNTED ON THE ATTENUATION RING. PETAL CHARACTERISTICS (135 mm LENGTH, 45 deg INCLINATION) DERIVED FROM CONTACT CONDITIONS AND CAPTURE STRATEGY.

  - **ATTENUATION SYSTEM** PROVIDES RESIDUAL ENERGY ATTENUATION CAPABILITY DURING DOCKING PROCESS. INDUCED LOADS DURING DOCKING LOWER THAN 500 N. PASSIVE ATTENUATION SYSTEM: NO DEDICATED DEPLOYMENT AND RETRACTION DEVICES. COMPRESSION OF ATTENUATION SYSTEM (15 mm "FLOATING" STROKE) IS PERFORMED BY CAPTURE LATCHES. ATTENUATION RING IS ALSO THE PUSHING ITEM DURING UNDOCKING TO PREVENT SEAL STICK.

  - **CAPTURE LATCHES** (FOUR UNITS LOCATED BEHIND PETALS AND MOUNTED ON THE MECHANISM MAIN STRUCTURE) DESIGNED FOR A "CAPTURE BEFORE CONTACT" STRATEGY. THIS LEADS TO A RELATIVELY LONG CAPTURE REACH (200 mm). CAPTURE LATCH STEPS: CAPTURE (TARGET RING CANNOT ESCAPE), APPROACH AND CENTERING, COMPRESSION OF ATTENUATION RING. DESIGN BASED ON FOUR-BAR LINKAGE CONCEPT PROVIDING FAST MOTION WHEN CAPTURING AND SLOW MOTION WHEN APPROACH.

  - **STRUCTURAL LATCHING SYSTEM** PROVIDES THE STRUCTURAL MATING OF BOTH SPACECRAFT TO ALLOW PRESSURISED PASSAGE. STRUCTURAL LATCHES HAVE TO COMPRESS SEALS BETWEEN BOTH DOCKING MECHANISM HALVES TO PROVIDE NECESSARY AIRTIGHTNESS AND TO SUPPORT PRESSURE LOADS (INTERNAL PRESSURE OF 1 atm IMPLIES 250,000 N SEPARATION FORCE). COMPATIBILITY WITH COLUMBUS FREE FLYER SYSTEM IMPOSES THE LATCH DESIGN CONCEPT AND NUMBER OF ATTACHMENT POINTS: 16 BOLT/NUT LATCHES. EACH LATCH IS DRIVEN BY A DEDICATED GEARMOTOR.


Guiding Petals
Attenuation Ring
Seals
Structural Latch
Capture Latch
Main Structure
Airlock (I/F)
Hatch
HERMES Docking Mechanism
Ready
For Capture
Capture Point
Capture Range
Attenuation Ring
Bolt (/ Nut)
Advance Screw
Housing
Spherical Bearing
Universal Joint
Spline
Driving Point

SENER

4. TECHNOLOGY INVESTIGATIONS ON DOCKING SYSTEMS AND DOCKING DYNAMICS

4.1 THE FRONT-END

* IN THE FRAME OF THE "RENDEZVOUS AND DOCKING PRE-DEVELOPMENT PROGRAMME" OF ESA, TECHNOLOGY INVESTIGATIONS ON DOCKING SYSTEMS AND DYNAMICS ARE CURRENTLY BEING PERFORMED. (SEE REF'S 5 & 6).

* SOME **OBJECTIVES** OF THE PROGRAMME ARE TO ASSESS ROBUSTNESS OF CONCEPTS INITIALLY SELECTED FOR HERMES AND COLUMBUS AND TO IDENTIFY SUITABLE IMPLEMENTATION SOLUTIONS THROUGH THE INVESTIGATION OF MAIN PARAMETERS DRIVING DBS FRONT-END CHARACTERISTICS:

  - APPROACH CONDITIONS: DIRECT DOCKING (HERMES-CFF), BERTHING (HERMES/CFF-SSF).
  - DYNAMICS: AXIAL/LATERAL FORCES AND TORQUES ON S/C DURING DOCKING/BERTHING, REBOUNDS,..
  - PERFORMANCES OF DBS FRONT-END ELEMENTS: GUIDING PETALS, ATTENUATION SYSTEM, CAPTURE LATCHES.

* **ISSUES** TO BE INVESTIGATED CONCERNING DBS FRONT-END FUNCTIONS:

  - GUIDANCE: GUIDING PETAL CONCEPT.
    - LOCATION (INTERNAL / EXTERNAL), NUMBER (3 / 4), SHAPE, INCLINATION, FRICTION BETWEEN PETALS WHEN CONTACT.

  - ATTENUATION:
    - STIFFNESS AND DAMPING CHARACTERISTICS AND RELATIONSHIP (AXIAL, LATERAL, BENDING, TORSION).
    - ROBUSTNESS WITH RESPECT TO CONTACT CONDITIONS AND RESULTING ATTENUATION STROKES AND LOADS.
    - ENERGY DISSIPATION AND TRANQUILLISATION TIMES.

  - CAPTURE: CAPTURE LATCH CONCEPT AND PERFORMANCES.
    - NUMBER (3 / 4) AND LOCATION (EXT / INT) OF CAPTURE LATCHES. CAPTURE RANGE AND SPEED.
    - CAPTURE STRATEGIES: BEFORE / AFTER CONTACT, WHEN TO CLOSE LATCHES ?.
    - CONFIGURATION: CAPTURE LATCHES IN CHARGE OF CLOSURE AND ATTENUATION SYSTEM RETRACTION (COMPRESSION) (CURRENT BASELINE), OR CAPTURE LATCHES MOUNTED ON ATTENUATION SYSTEM.

* FOLLOWING THE ABOVE OBJECTIVES A **DBS FRONT-END MODEL** HAS BEEN DESIGNED, BUILT AND CALIBRATED. THIS MODEL WILL BE TESTED AT THE "DOCKING DYNAMICS TEST FACILITY" AT MATRA (FRANCE). SOFTWARE SIMULATIONS WILL BE PERFORMED BY USING THE "DOCKING SIMULATION PROGRAM" TAKING INTO ACCOUNT THE ACTUAL PERFORMANCES OF DBS FRONT-END MODEL FOR CROSS COMPARISON AND VALIDATION "DSP".

DBS FRONT-END MODEL CHARACTERISTICS

* DBS FRONT-END MODEL (DBS-FEM) IS A MODULAR TOOL FOR SIMULATION OF DOCKING/BERTHING SYSTEMS. ITS UTILISATION FLEXIBILITY ALLOWS TO COVER THE EXPECTED RANGE OF CONDITIONS OF THE SCENARIOS.

* IT CONSISTS OF TWO PARTS: THE ACTIVE PART (CHASER) AND THE PASSIVE PART (TARGET).

* MAIN CONSTRAINTS IMPOSED BY THE DDTF:
  - SIZE OF THE DBS-FEM IS ABOUT 0.5 - 0.6 TIMES THE SIZE OF THE CURRENT CONCEPTS OF DBS FOR HERMES AND COLUMBUS.
  - MASS OF DBS-FEM IS LIMITED TO 250 kg (CHASER) AND 75 kg (TARGET).

* MAIN ELEMENTS OF THE FRONT-END MODEL:

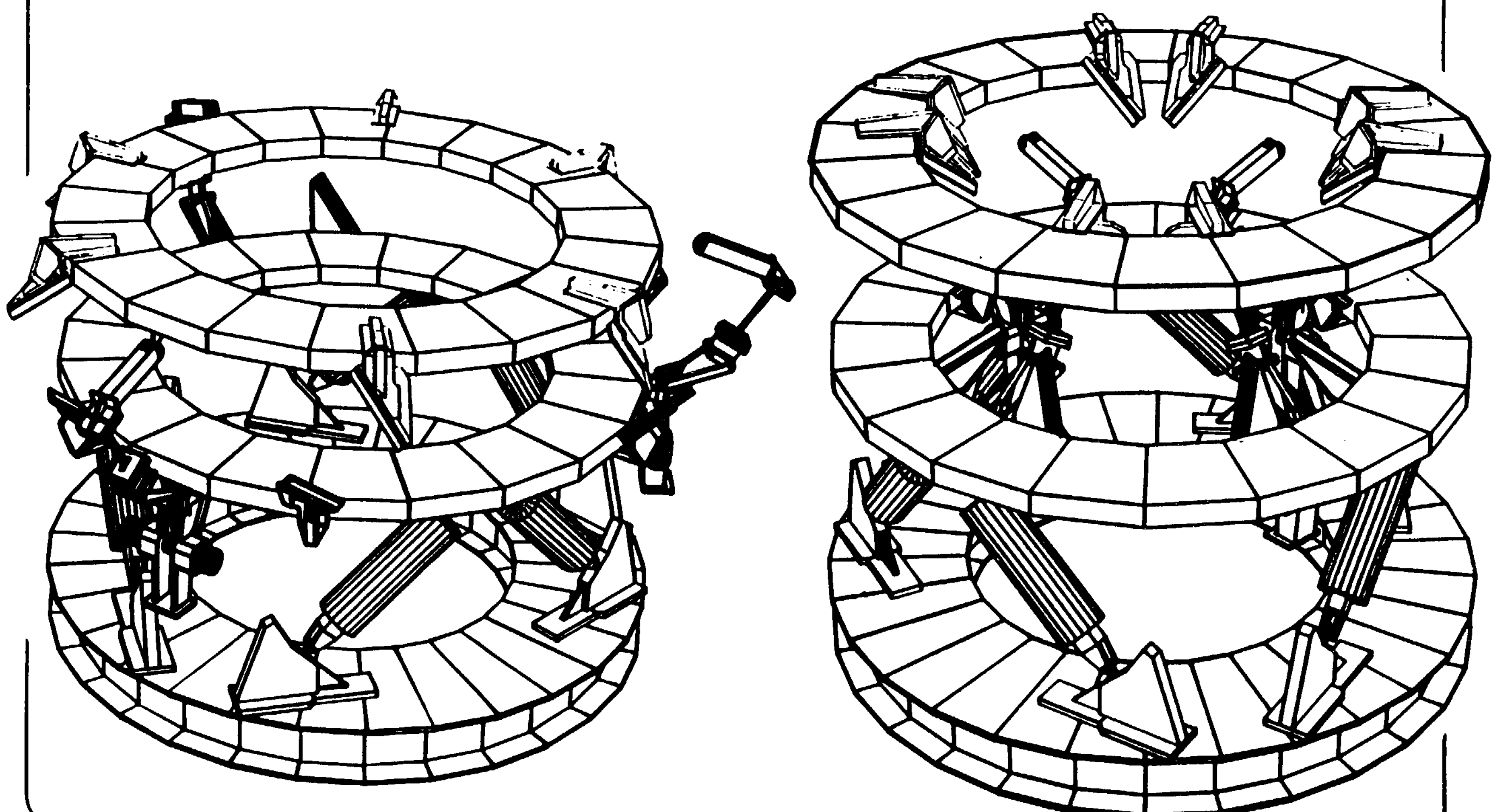
  * **SUPPORT FLANGE** IS THE STRUCTURAL I/F WITH THE DDTF FIXED PART THROUGH THE FORCE DETECTOR RODS. ATTENUATION SYSTEM IS MOUNTED ON THIS ELEMENT. STRUCTURAL ELEMENTS HAVE BEEN DESIGNED TO PROVIDE A STIFFNESS 20 TIMES HIGHER THAN THE MAXIMUM ONE OF THE ATTENUATION SYSTEM SO THAT DYNAMICS ARE GOVERNED JUST BY THE ATTENUATION SYSTEM CHARACTERISTICS.

  * **ATTENUATION RINGS (DOCKING RINGS)** ARE PROVIDED IN BOTH CHASER AND TARGET. TARGET RING IS MOUNTED ON THE DDTF MOVING PART AND CHASER RING IS MOUNTED ON THE ATTENUATION SYSTEM. DOCKING RINGS ALLOW EITHER INTERNAL OR EXTERNAL MOUNTING OF THE CAPTURE LATCHES AND GUIDING PETAL SETS, WITH 3 OR 4 PETAL CONFIGURATION.

  * **ATTENUATION SYSTEM** CONSISTS OF SIX SPECIALLY DESIGNED SINGLE DAMPERS. ATTENUATION SYSTEM CHARACTERISTICS (STIFFNESS & DAMPING RATES) CAN BY TUNED BY: CHANGING THE INCLINATION OF THE DAMPERS (30/45/60 deg) AND TUNING DAMPER CHARACTERISTICS.
    DAMPING RATES FOR EACH SINGLE DAMPER CAN BE TUNED FROM 10,000 Ns/m TO 150,000 Ns/m.
    TYPICAL VALUES OF STIFFNESS OF EACH DAMPER WILL BE 1.6E4 N/m, 4.0E4 N/m, 7.5E4 N/m AND 14E4 N/m.
    THE SYSTEM ALLOWS THE INVESTIGATION OF THE DBS BEHAVIOUR W.R.T. AND THE RELATIONSHIP OF THE FOLLOWING PARAMETERS:
    - CONTACT VELOCITIES WHEN DOCKING (APPROACH, LATERAL, ROLL, PITCH/YAW), ATTENUATION SYSTEM PERFORMANCES (STIFFNESS, DAMPING RATES), VS,
    - LOADS/DISTURBANCES DURING DOCKING, REBOUNDS EFFECTS (DIRECTION, VELOCITIES), ATTENUATION STROKES, TRANQUILLISATION TIMES,..

    EACH DAMPER IS PROVIDED WITH LINEAR SENSORS TO KNOW THE POSITION OF THE ATTENUATION RING.

DBS FRONT-END MODEL



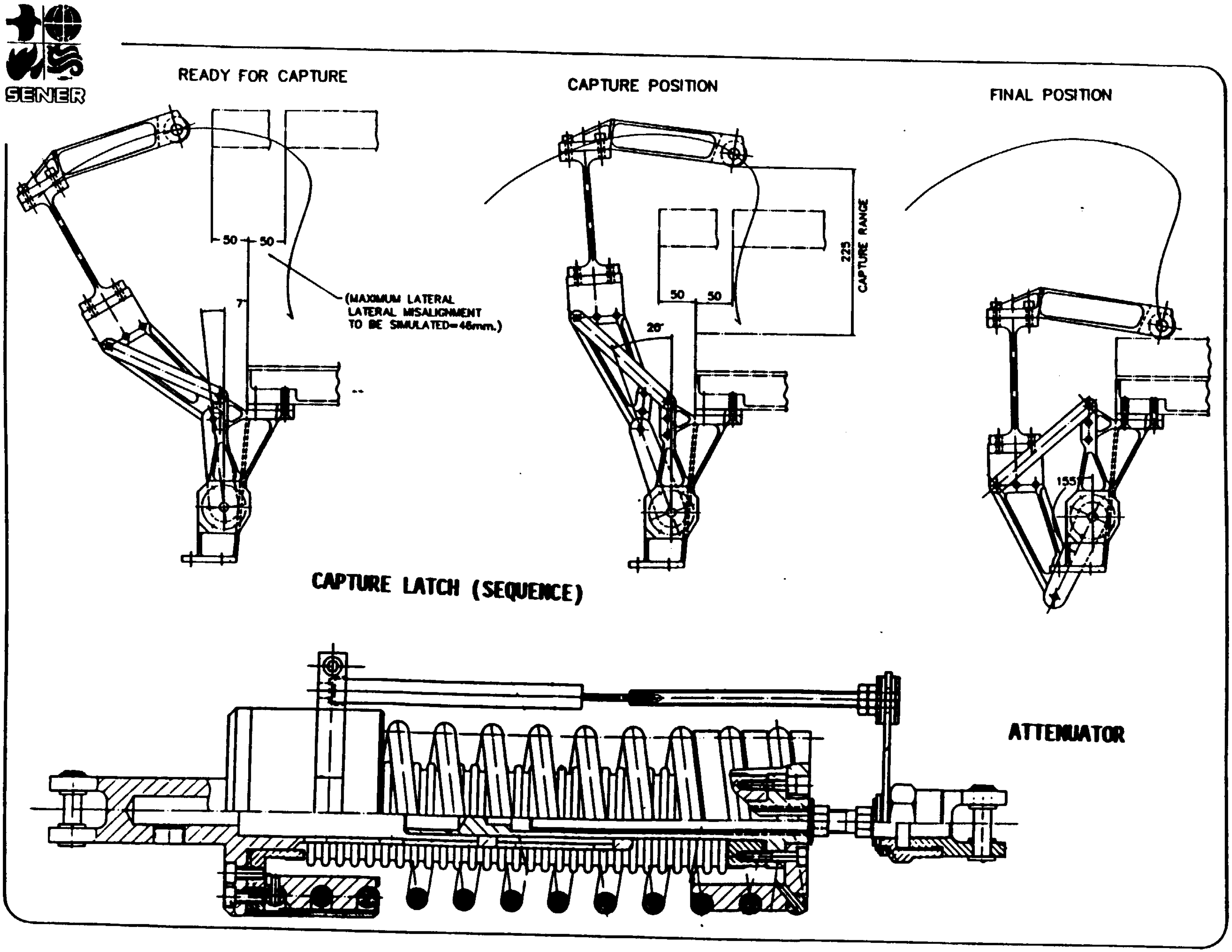
SENER

* **GUIDING PETALS** ARE DESIGNED TO COPE WITH APPROACH CONDITIONS (MISALIGNMENTS, VELOCITIES) SIMULATED BY DDTF. EACH GUIDING PETAL CONSISTS OF TWO HALVES. THE ORIENTATION OF THE PETAL EDGE IS THE PARAMETER DEFINING THE CHARACTERISTICS OF THE PETAL. EACH PETAL CAN BE ORIENTED TO HAVE INCLINATIONS OF 30/45 deg W.R.T. THE DOCKING AXIS AND 30/45 deg (EXT) OR 20/35 deg (INT) W.R.T. THE DOCKING PLANE RADIUS.
  LOW VALUES OF THE PETAL INCLINATION ALLOW BETTER ALIGNMENT DURING MATING BUT IMPLY HIGHER DISTANCE BETWEEN DOCKING RINGS WHEN FIRST POSSIBLE CONTACT, THEREFORE HIGHER CAPTURE RANGES REQUIRED FOR THE CAPTURE LATCHES.

* **CAPTURE LATCHES:** THE INVESTIGATION OF THE CAPTURE PARAMETERS (STRATEGY, CAPTURE AND APPROACH SPEEDS, CAPTURE RANGES,...) IMPOSES A MODULAR DESIGN OF THE LATCHES WITH TUNING CAPABILITY OF THE OPERATING VELOCITIES AND CAPTURE RANGES. LATCH POSITION AND VELOCITIES WILL BE CONTROLLED BY THE CONTROL ELECTRONIC UNIT.
  THREE MAJOR STEPS DURING THE CAPTURE LATCH OPERATION:
  - **CAPTURE**, MOTION FROM INITIAL POSITION (OPEN) TO CAPTURE POSITION (TARGET RING CAN NOT ESCAPE). THE LOWER CAPTURE RANGE THE FASTER CAPTURE VELOCITY. CAPTURE TIMES FROM 1.0 s WILL BE STUDIED.
  - **APPROACH** OF BOTH DOCKING RINGS, LATCH MOTION FROM CAPTURE POINT TO MATING POINT (BOTH RINGS MATCHED). LATCH MOTION SHALL BE SUFFICIENTLY LOW TO AVOID INCREASING OF KINETIC ENERGY AND CONTACT FORCES AND LEVEL OF DISTURBANCES. MAXIMUM APPROACH VELOCITIES IN THE RANGE 5 mm/s TO 1 mm/s WILL BE STUDIED.
  - **LATCHING**, LATCHING FORCE (PRELOAD) IS REQUIRED TO PROVIDE THE MATING I/F OF THE COMPOSITE S/C WITH A MINIMUM STIFFNESS. DYNAMICS AFTER MATING DEPEND ON THE STRUCTURAL CHARACTERISTICS OF THIS I/F AND INERTIAL PROPERTIES OF THE S/C.

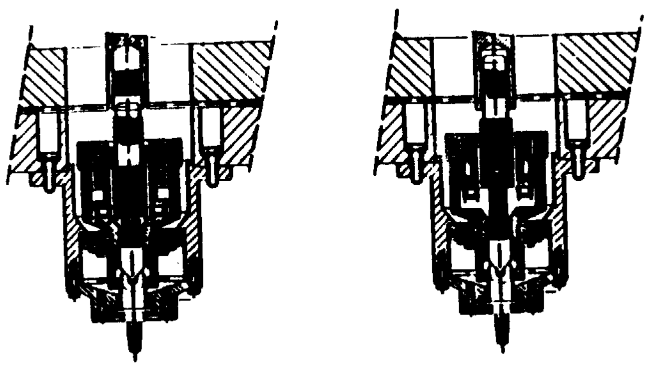
  CAPTURE RANGE (DISTANCE FROM CAPTURE POINT TO CHASER RING) DEPENDS ON THE CAPTURE STRATEGY, THE CAPTURE VELOCITY, DOCKING CONDITIONS (VEL., MISALIGN.), REBOUNDS, ETC. CAPTURE BEFORE CONTACT STRATEGY IS THE PREFERRED ONE BUT LEADS TO HIGH CAPTURE RANGES AND BIG LATCHES. CAPTURE LATCHES ALLOW TUNING OF CAPTURE RANGE FROM 250 mm TO LOWER. (250 mm IN THE DBS-FEM MEANS 500 mm FOR THE ACTUAL DBS SIZE).
  CAPTURE LATCHES CAN OPERATE IN DIFFERENT VELOCITIES IN CAPTURE AND IN APPROACH, BEING BOTH VELOCITIES INDEPENDENTLY TUNED FROM THE CONTROL ELECTRONIC UNIT.

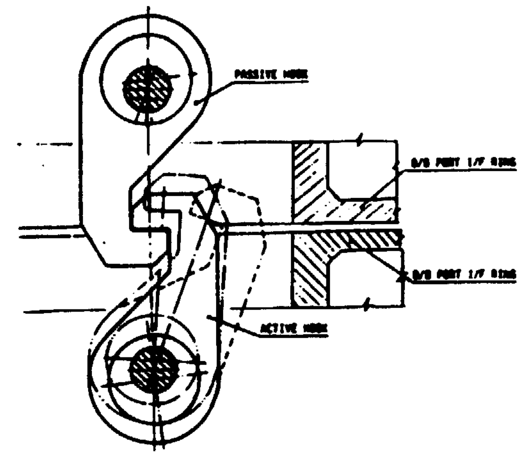
  CAPTURE LATCHES CAN EITHER MOUNTED ON THE ATTENUATION RING (WHEN LONG ATTENUATION STROKES AND SYSTEMS REQUIRING ACTIVE DEPLOYMENT/RETRACTION OF DOCKING RING) OR ON THE FIXED STRUCTURE (WHEN SHORT ATTENUATION STROKES, < 20 mm, RETRACTION OF ATTENUATION RING PERFORMED BY THE LATCHES).


SENER
READY FOR CAPTURE
50
50
7°
(MAXIMUM LATERAL
LATERAL MISALIGNMENT
TO BE SIMULATED=46mm.)
CAPTURE POSITION
225
CAPTURE RANGE
50
50
20°
FINAL POSITION
155
CAPTURE LATCH (SEQUENCE)
ATTENUATOR

4.2 THE STRUCTURAL LATCHING

STRUCTURAL LATCHES HAVE TO CARRY OUT THE MECHANICAL RIGIDIZATION OF THE COMPOSITE (HERMES-CFF) IN THE DOCKED MODE. CURRENT BASELINE IS BASED ON THE BOLT-NUT CONCEPT BECAUSE OF COMPATIBILITY WITH SSF, HOWEVER OTHER CONCEPTS LIKE HOOK-HOOK ARE BEING ANALYSED.





4.3 THE SEALING

SEALING SYSTEM HAS TO PROVIDE NECESSARY AIRTIGHTNESS TO THE PRESSURISED PASSAGEWAY BETWEEN BOTH S/C.

SEALING SYSTEMS ARE BEING INVESTIGATED TO BE IMPLEMENTED IN DOCKING/BERTHING MECHANISMS AND HATCHES OF HERMES AND COLUMBUS ELEMENTS.

STUDIES AND DEVELOPMENT TASKS ARE FOCUSED TO THE FOLLOWING MAIN ISSUES:

- TO OBTAIN LEAK RATES FOR DIFFERENT SEALING SYSTEMS, AND CORRELATION WITH RELATIVE DEFLECTION AT SEALING INTERFACES.
- SEALING PERFORMANCES TAKING INTO ACCOUNT: SEALING SYSTEM (MATERIALS, SURFACE CHARACTERISTICS, ENVIRONMENTAL CONDITIONS, LIFE CYCLING, REDUNDANCY,..)
- ON-ORBIT LEAK VERIFICATION PROCEDURES.
- LIFE AND MAINTENANCE (SPECIALLY CRITICAL IN CASE OF CFF).
- OPERATIONAL ASPECTS AND RELATIONSHIP WITH OTHER DBS ITEMS: STRUCTURAL STIFFNESS VS MASS VS RELATIVE DEFLECTION, NUMBER OF STRUCTURAL LATCHES VS MASS VS FAILURE TOLERANCE,..

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4. M. LE DU, (1990). "OVERVIEW OF CNES RENDEZVOUS AND DOCKING ACTIVITIES". AUTONOMOUS RVD CONFERENCE, HOUSTON (USA).

5. J.M. PAIROT, C. PAUVERT, (1990). "DOCKING MECHANISM DESIGN: ANALYSIS OF THE FRONT-END REQUIREMENTS AND VERIFICATION TOOLS".
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6. J.M. PAIROT, C. PAUVERT, (1990). "HERMES AND COLUMBUS RV CONTROL SYSTEM". AUTONOMOUS RVD CONFERENCE, HOUSTON (USA).

ACTIVITIES REPORTED IN THIS PRESENTATION HAVE BEEN PERFORMED IN THE FRAME OF THE **HERMES** AND **COLUMBUS** PROGRAMMES AND OF THE TECHNOLOGY PROGRAMMES OF THE EUROPEAN SPACE AGENCY.

INVESTIGATIONS ON SEALING SYSTEMS HAVE BEEN ALSO PERFORMED IN THE FRAME OF THE SPANISH NATIONAL SPACE PLAN AND TECHNOLOGY DEVELOPMENTS OF SENER.

ACKNOWLEDGEMENTS

THE AUTHORS WANT TO THANK THEIR NUMEROUS COLLEAGUES IN **ESA**, **SENER**, **MATRA**, **CNES**, **DORNIER** AND **AERITALIA** FOR THE CONTRIBUTION TO THE INVESTIGATIONS REPORTED IN THIS PRESENTATION.

OPTICAL POSITION SENSOR DEVELOPMENT AT JPL

PRESENTED TO

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

JOHNSON SPACE FLIGHT CENTER
AUGUST 15-16, 1990

PREPARED BY
N.Nerheim and R. Bartman
Optoelectronics Sensor Systems and Technology Group

With thanks to G. Sevaston for presenting

OPTICAL POSITION SENSOR DEVELOPMENT AT JPL

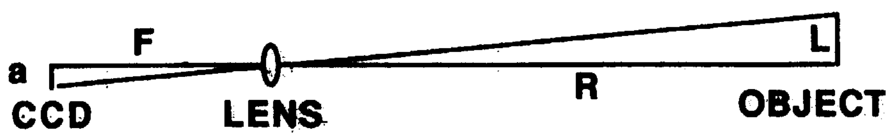
TOPICS

- **CCD-BASED TACHYMETER**
  Range determination from image size

- **LATERAL CELL ANGULAR POSITION SENSOR**
  An alternative to the CCD

- **SHAPES** (SPATIAL, HIGH-ACCURACY, POSITON-ENCODING SENSOR)
  Simultaneous measurement of the 3-D position of multiple targets

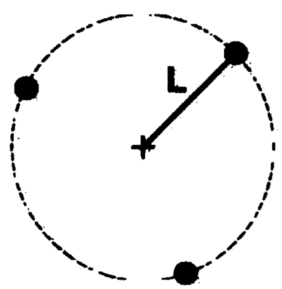
RANGE ESTIMATION FROM IMAGE SIZE OF A KNOWN OBJECT (TACHYMETER)



R = Range
L = Known Dimension
F = Focal Length
a = Image of L

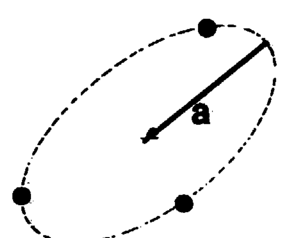
$$R = FL/a \qquad (1)$$

$$(\sigma_R/R)^2 = (\sigma_F/F)^2 + (\sigma_L/L)^2 + (\sigma_a/a)^2 \qquad (2)$$



Normal View of Target array

TARGETS ARE ILLUMINATED RETROREFLECTORS OR BEACONS ARRANGED AS EQUILATERAL TRIANGLE (INSCRIBED IN CIRCLE OF RADIUS L)



Sensor View of Target array

PROBLEM: RELATE CENTROIDS OF 3 IMAGES TO L AND CALCULATE R FROM (1)

SOLUTION: DETERMINE MAJOR AXIS , a, OF ELLIPSE

(DETERMINATION OF TILT DIRECTION REQUIRES ADDITIONAL RETROREFLECTOR/BEACON)

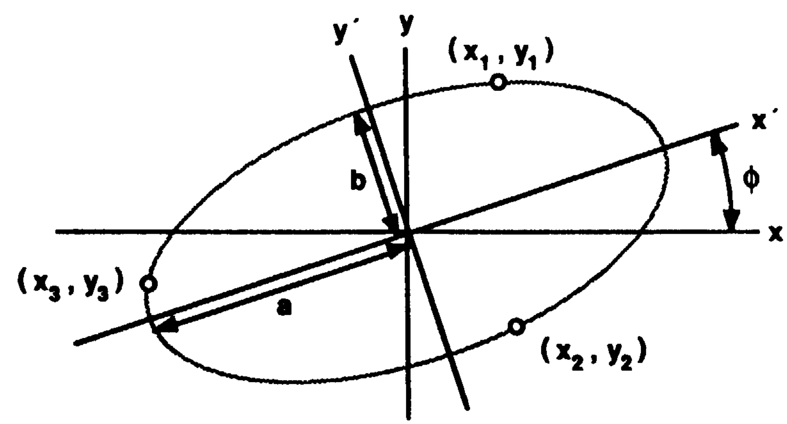
Range Estimation from Image Size

Range may be estimated from measurements of the image size of a known object formed on the CCD detector of a solid state camera. The known object consists of three targets, either beacons or retroreflectors, arranged as an equilateral triangle inscribed in a circle of known radius. In general, the image appears as three points on an ellipse with a major axis that corresponds to the target array radius. The problem is to determine the major axis from the CCD images with sufficient accuracy to achieve the desired range accuracy.

As demonstrated with CCD-based star trackers, image position on a CCD can be determined with an error of about 0.01 pixels. It is shown that the accuracy of range determined from measurements based on a read error of 0.01 pixels from a sufficiently large CCD is sufficient for docking operations.

The maximum range at which a measurement can be made occurs when the three images appear with sufficient separation for accurate centroid calculation. The images just fill the CCD at minimum range.

Range Estimation from Image Size



- **Determine Major Axis, a**
  - Locate center of ellipse; translate origin of coordinate system to coincide
  - Find coefficients A,B,C of $Ax^2 + Bxy + Cy^2 = 1$ as a function of the image coordinates x_i, y_i
  - Rotate coordinate system to align with minor, major axes

$$x' = x \cos\phi + y \sin\phi$$
$$y' = -x \sin\phi + y \cos\phi$$

Then $(x'/a)^2 + (y'/b)^2 = 1$

  - Solve for a,b and ϕ
    - $2/a^2 = A + C - \sqrt{(A - C)^2 + B^2}$
    - $2/b^2 = A + C + \sqrt{(A - C)^2 + B^2}$
    - $\tan 2\phi = B/(A-C)$
  - Error analysis of the above indicates $\sigma_a \approx 3\sigma_x$, where σ_x = image centroiding error

RANGE ESTIMATION FROM IMAGE SIZE

SAMPLE RESULTS

ASSUME: 1024 x 1024 CCD

σ_x = 0.01 PIXELS (Image Covers 3x3 Pixels)

L = 1 m

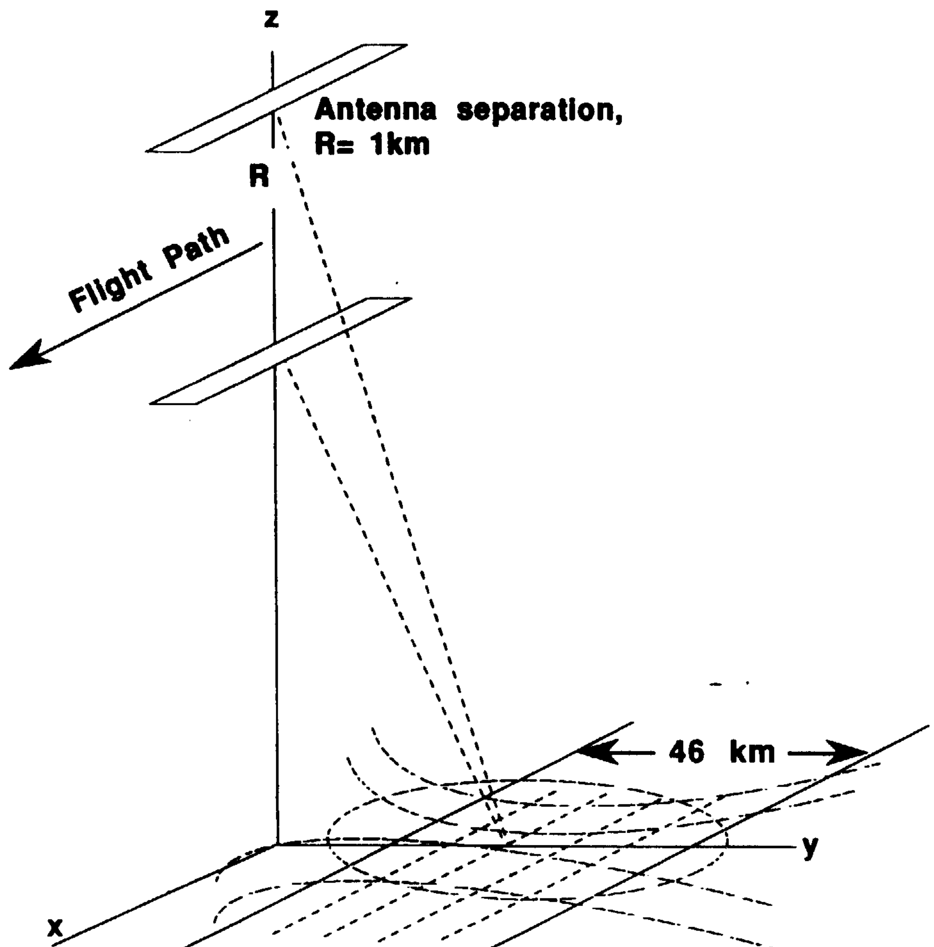
	FOV = 10 deg.	FOV = 5 deg.
Max. Range (a = 5 pixels)	R = 1.1 km	R = 2.3 km
	σ_R = 7 m	σ_R = 14 m
Min. Range (a = 500 pixels)	R = 11.4 m	R = 23 m
	σ_R = 0.7 mm	σ_R = 1.4 mm

The minimum range can be reduced by a second set of reflectors/ beacons with reduced spacing. (e.g., if L = 10 cm, R_{min} = 1 m.)

ANTENNA POSITION SENSOR FOR GLAM-VISTA

(Global Land/Ice Altimeter Mission -Vertical Interferometer SAR Tethered Altimeter)

Misson Objective: Topographic Mapping of Earth



Vertical Arrangement of GLAM-VISTA Antennas

<u>GLAM-VISTA MISSION</u>

- Complete Global mapping in 3 months
- Vertically separated antenna mounted on 2 tethered satellites
- Mapping Resolution
  - Spatial: 30 m x 33 m
  - Height: 2 m

GLAM-VISTA ANTENNA POSITION SENSORS

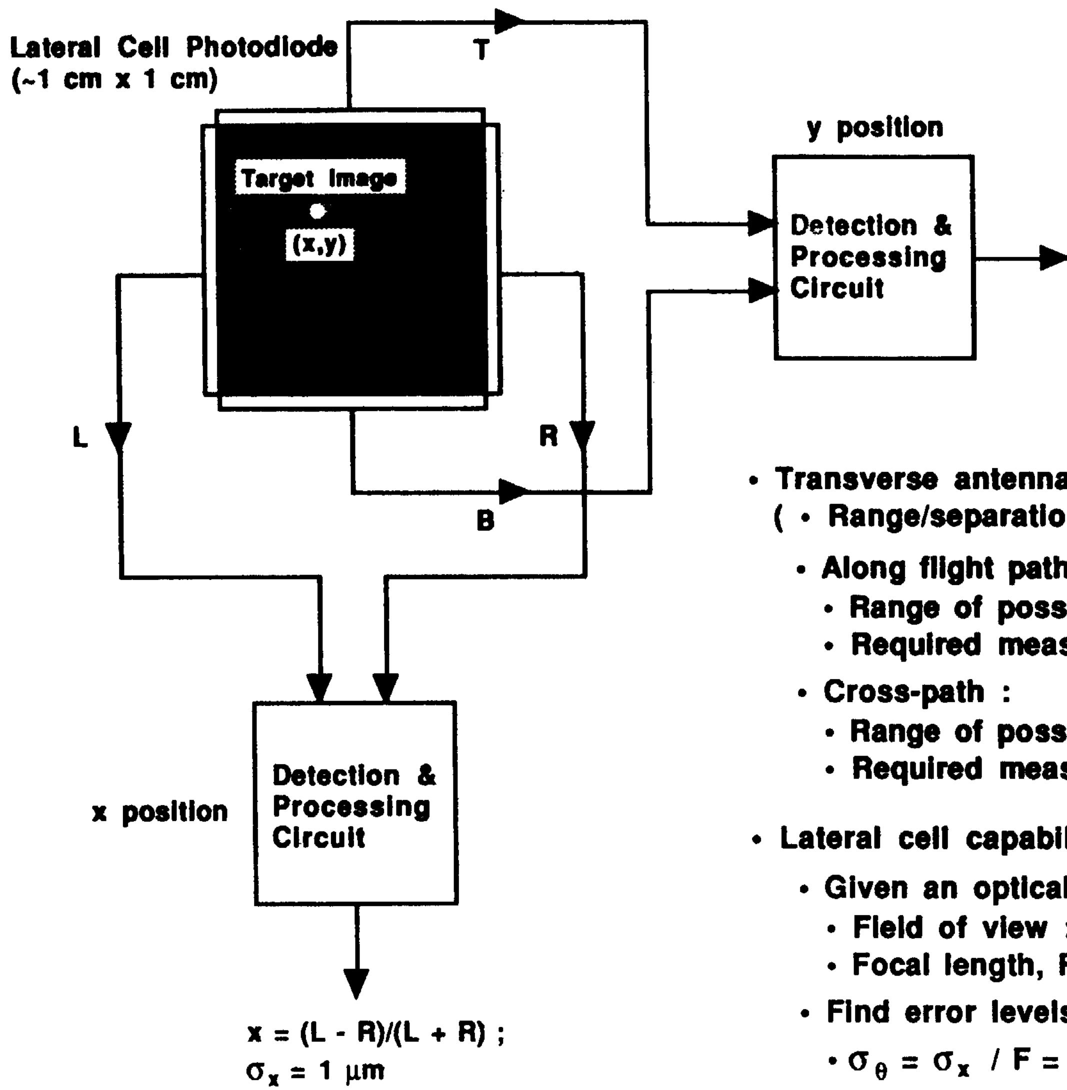
A proposed mission to map the earth using synthetic aperature radar makes use of two microwave antennas maintained with a fixed separation. In one configuration, the antennas are oriented vertically with a 1 km tether connecting them. The satellilte carrying one of he antennas also carries the navigation center; hence, its position and attitude is known at all times. To achieve the required mapping accuracy, the position of the second antenna must be known with millimeter accuracy.

- Antenna Separation
  - Distance: R = 1km
  - Required accuracy: $\sigma = 2.3$ mm
- Relative Lateral Position of Antennas
  - Range of motion : 1 m x 12 m
  - Required accuracy : $\sigma = 5$ mm

The range measurement can be made with a conventional beam-modulated optical range finder and is not discussed here.

The relative lateral position of the second antenna may be determined from the known range and a measured angular position. The angular position may be determined with a camera equipped with a CCD detector, or as examined here, with a lateral-effect photodetector.

Lateral Cell Photodiodes - Measuring transverse position of a single target



- Transverse antenna position measurements for GLAM - VISTA
  (• Range/separation is measured with a laser rangefinder)
  - Along flight path :
    - Range of possible motion : 12 m
    - Required measurement accuracy : 5 mm
  - Cross-path :
    - Range of possible motion : 1 m
    - Required measurement accuracy : 5 mm
- Lateral cell capabilities
  - Given an optical design with :
    - Field of view : 1.4 degrees
    - Focal length, F : 0.4 mm
  - Find error levels / potential accuracies of :
    - $\sigma_\theta = \sigma_x / F = 1\ \mu m / 0.4\ m = 2.5\ \mu rad$
    - $\sigma_{transverse} = R\sigma_\theta = 1\ km \times 2.5\ \mu rad = 2.5\ mm$

    where R = antenna separation

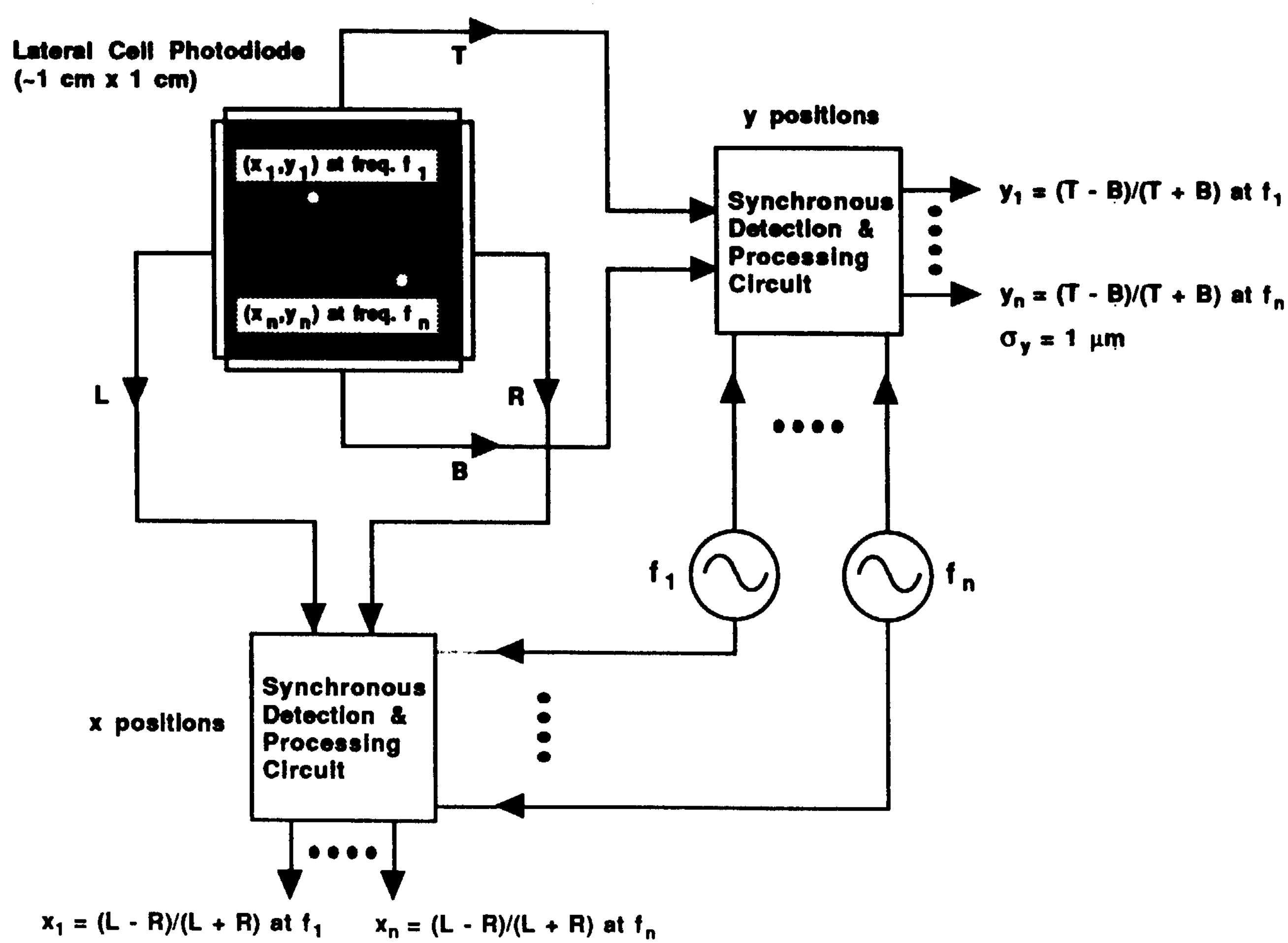
Lateral Cell Photodiode

The lateral-effect photodiode is a relatively new type of position-sensing detector. This device provides a direct readout of the displacement of a light spot on its active area. With the aid of optics and electronics, the lateral cell can be used to measure the angular position of a target in much the same way that a CCD camera is used. Although not as accurate as the CCD, the lateral cell and the required data processing circuits are much simpler. The lateral cells are typically used for single targets, but the concept can be extended to include multiple targets.

Carriers produced by the photons that strike the active surface produce photo currents that flow to the contacts located on all four sides of the cell. The location of the centroid of the light spot is found from the relative magnitude of the currents from each contact as indicated on the facing page. The position error of a 10x10 mm cell can be as small as 1 μm, which, for the proposed application results in a 2.5 mm position error in the measurement of the transverse location of one antenna relative to the other.

Lateral Cell Photodiodes - Measuring transverse positions of multiple targets

- Light from target "k" is amplitude-modulated at frequency f_k
- Use synchronous detection to measure lateral cell output at f_k ; Output at f_k provides coordinates x_k, y_k
- Maximum modulation frequency (~ 10-15 kHz) determined by capacitance of lateral cell
- Maximum number of targets determined by resolvable frequency separation and/or saturation of lateral cell



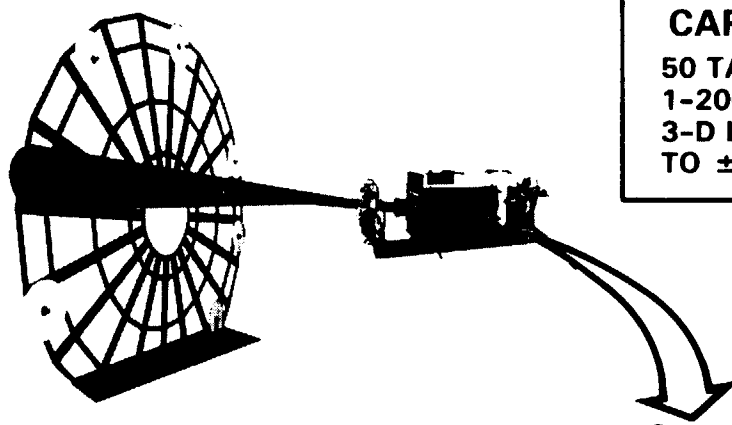
Multiple Image Lateral-Effect Photodiode

The operating proceedure of a position sensor equipped with a lateral cell detector can be modified to extend its use from single target operation to multi-target operarion by modulating the light intensity from each of the targets at separate frequencies. A synchronous detection system with a narrow bandwidth centered about the modulation frequency of each illuminator is used to isolate the signal from each target. The number of targets that can be observed depends on the saturation level of the cell as well as the resolution bandwidth of each signal.

The multi-target lateral-cell detector is being developed at JPL for the Astronautics Laboratory, Air Force Systems Command, as a position sensor for the Multi-body Dynamics Experiment Facility at Edwards Air Force Base. The sensor is designed to measure position of points on a highly flexible structure used for validation of control algorithms.

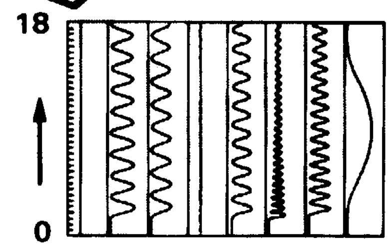
SHAPES: SPATIAL, HIGH-ACCURACY, POSITION ENCODING SENSOR

MULTI-TARGET RANGING DEMONSTRATION

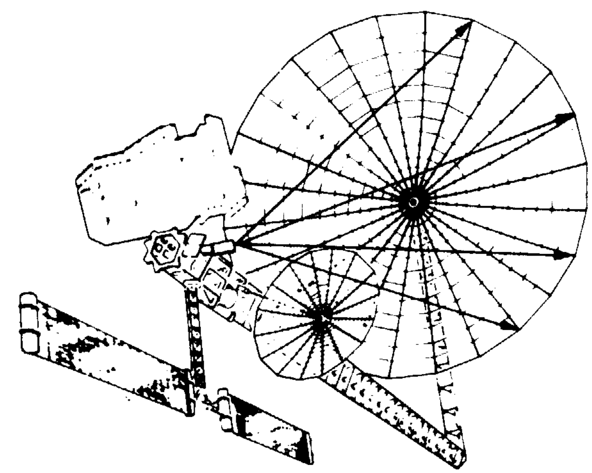


CAPABILITY GOALS

50 TARGETS
1-200 meter RANGE
3-D LOCATION
TO ±0.1 mm ACCURACY



TARGET MOTION



ACCOMPLISHMENT
SIMULTANEOUS RANGING

- NUMBER OF TARGETS 16
- FRAMING RATE 10 Hz
- POSITION RESOLUTION 0.1 mm

PAYOFF

SENSING FOR STATIC SHAPE AND DYNAMIC CONTROL OF LARGE STRUCTURES

SHAPES

SHAPES, an acronym for Spatial, High-Accuracy, Position-Encoding Sensor, provides simultaneous, high accuracy measurements of a relatively large number of targets . This capability is required in system identification and control of large flexible structures, such as large antennas, and will also prove valuable in automated rendezvous and docking applications.

A range-only laboratory version of SHAPES has been built and demonstrated. The instrument ranges to 16 targets with resolution of 100 μm at update rates of 10 Hz. The range-only design has been extended to include angular measurements to provide three-dimensional position sensing, and to increase the number of targets and the FOV.

Fabrication of a 3-D breadboard, capable of full three-dimensional position measurements at the above performance levels is completed. The instrument uses a multi-processor data acquisition and experiment control system to correlate the range and angular measurements.

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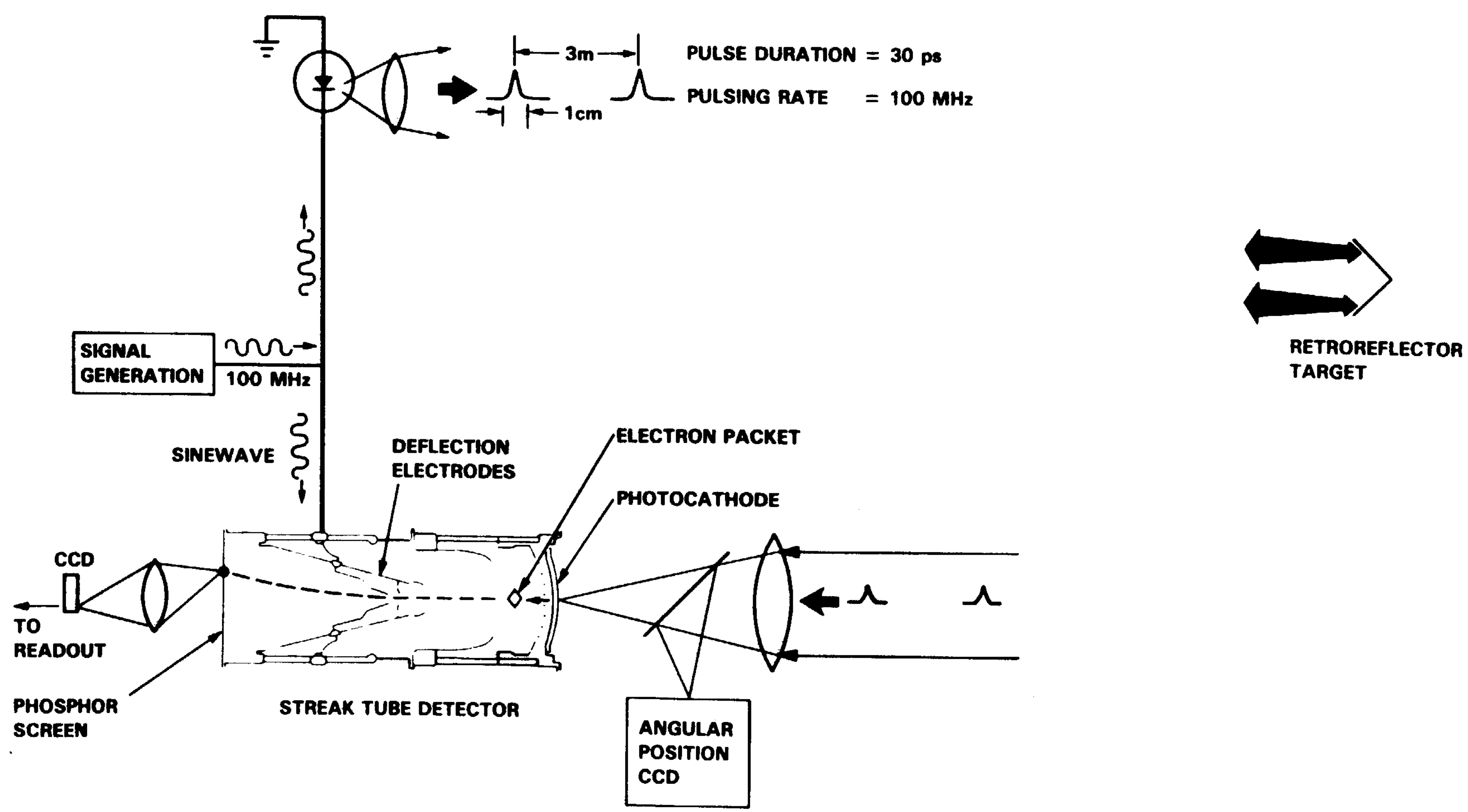
SHAPES OPERATING PRINCIPLE



SHAPES

SHAPES Ranging Principle

SHAPES determines a target's position in terms of range and two angular coordinates. The ranging function is performed by a system based on a streak tube camera and a set of picosecond-pulsed semiconductor lasers. In broad terms, the streak camera measures the range-related phase shift between a "psuedo-wave", represented by a train of picosecond laser pulses, and a reference sine wave which drives the camera's deflection plates. The angular position is determined with a CCD camera in combination with a laser-illumination system. The angular system is similar in operation to CCD-based star-trackers, but requires significantly higher update and data processing rates.

The SHAPES operating wavelength, λ, is the distance separating the laser pulses. At the SHAPES operating frequency of 100 MHz, the wavelength is 3 m. The range measurement, in is analogy with conventional optical interferometry, is ambiguous beyond $\lambda/2$. However, by operating at two successive frequencies, the range of unambiguous measurement (the ambiguity length) can be significantly increased. Operation at two frequencies that differ by 1% results in a "synthetic" wavelength of 300 m and an ambiguity length of 150 m. Once the target is acquired, it is tracked at a single operating frequency.

JPL

SIMULTANEOUS RANGING TO MULTIPLE TARGETS WITH SHAPES

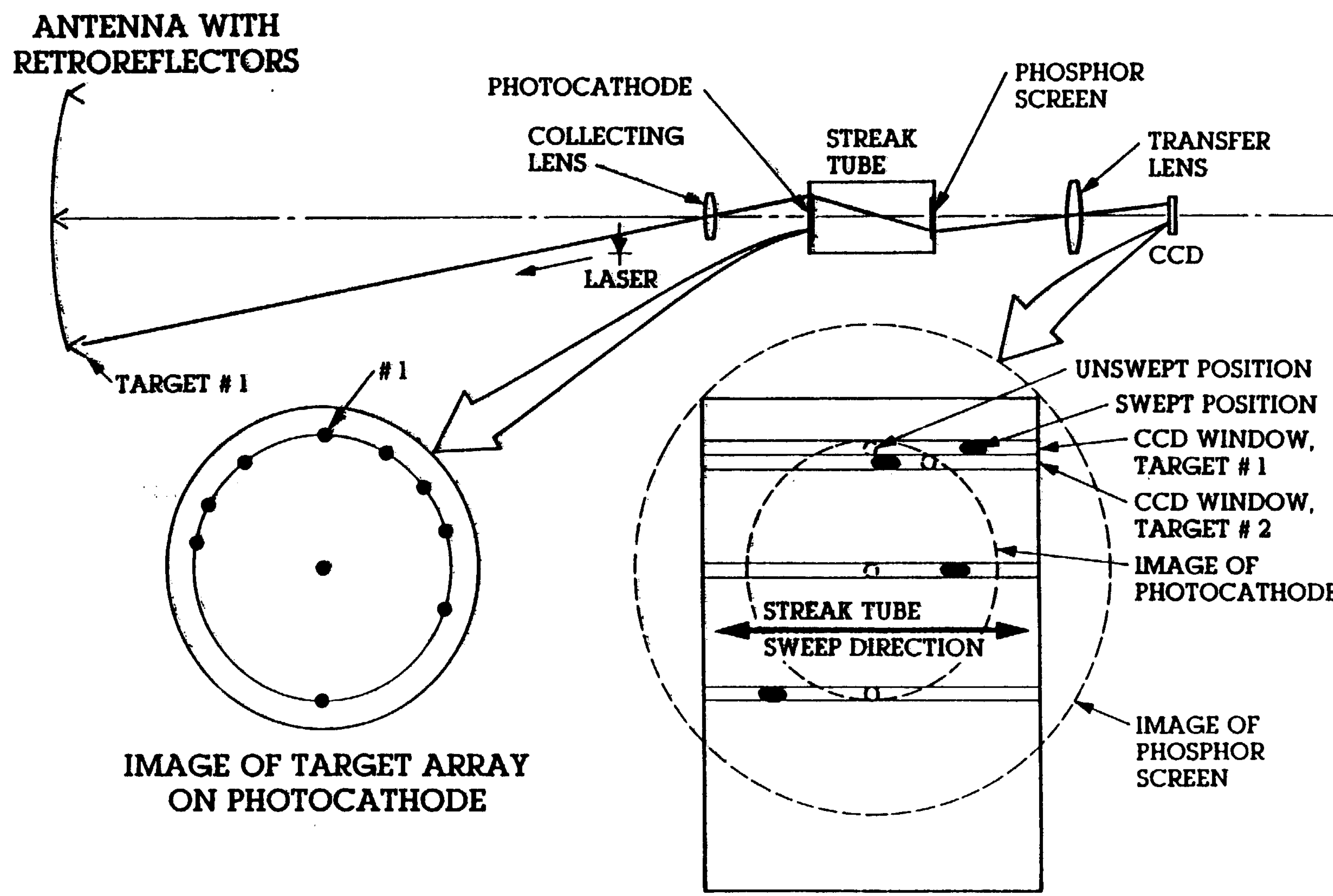


IMAGE OF TARGET ARRAY ON PHOTOCATHODE

IMAGE OF PHOSPHOR SCREEN ON CCD

SHAPES

Simultaneous Ranging to Multiple Targets

The target area is illuminated with pulsed lasers for a period of about 10 ms. Return optical pulses from each target are focused unto the streak tube photocathode and produce an image on the CCD detector at a position that depends on the image location on the streak tube photocathode and on the range of the target . Following the illumination period, the CCD detector data are processed to provide the location of the images on the CCD. The difference between the "unswept" (zero drive voltage) and "swept" position is a function of the target range.

An operating requirement is that images do not overlap on the CCD, a condition that limits the number of targets that can be observed: the maximum number of targets is determined by the size of the images and the size of the streak tube photocathode. The present streak tube uses a 10 mm photocathode and is capable of simultaneously ranging to 24 targets .

An alternate illumination system features a Remote Optical Head. Optical fibers transmit the illuminating laser pulses to the Remote Head, collect the return pulses, and transmit them to the streak tube. The Remote Head is entirely passive and may be located at any convenient location on the structure to be measured.

SHAPES 3-D BREADBOARD

DEMONSTRATION OBJECTIVES

• NUMBER OF TARGETS	24
• DATA UPDATE RATE	10 Hz
• RESOLUTION (1σ)	
• RANGE	100 μm
• ANGULAR	50 μrad
• FOV	32 deg
• MEASUREMENT RANGE	0 - 50 m
• TARGET VELOCITY	
• RANGE	10 cm/sec
• ANGULAR	50 mrad/sec

SHAPES 3-D BREADBOARD

STATUS

- 3-D BREADBOARD FAB COMPLETED FY90
- 3-D TRACKING OF SINGLE TARGET DEMONSTRATED
- TASK COMPLETION IN FY 91
    - DEMONSTRATE TRACKING OF 24 TARGETS AT 10 HZ
    - COMPLETE SENSOR CHARACTERIZATION
    - COMPLETE TECHNOLOGY TRANSFER TO INDUSTRY

Docking Mechanism Design : Analysis of Front-End Requirements & Verification Tools

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INGENIERIA Y SISTEMAS S A

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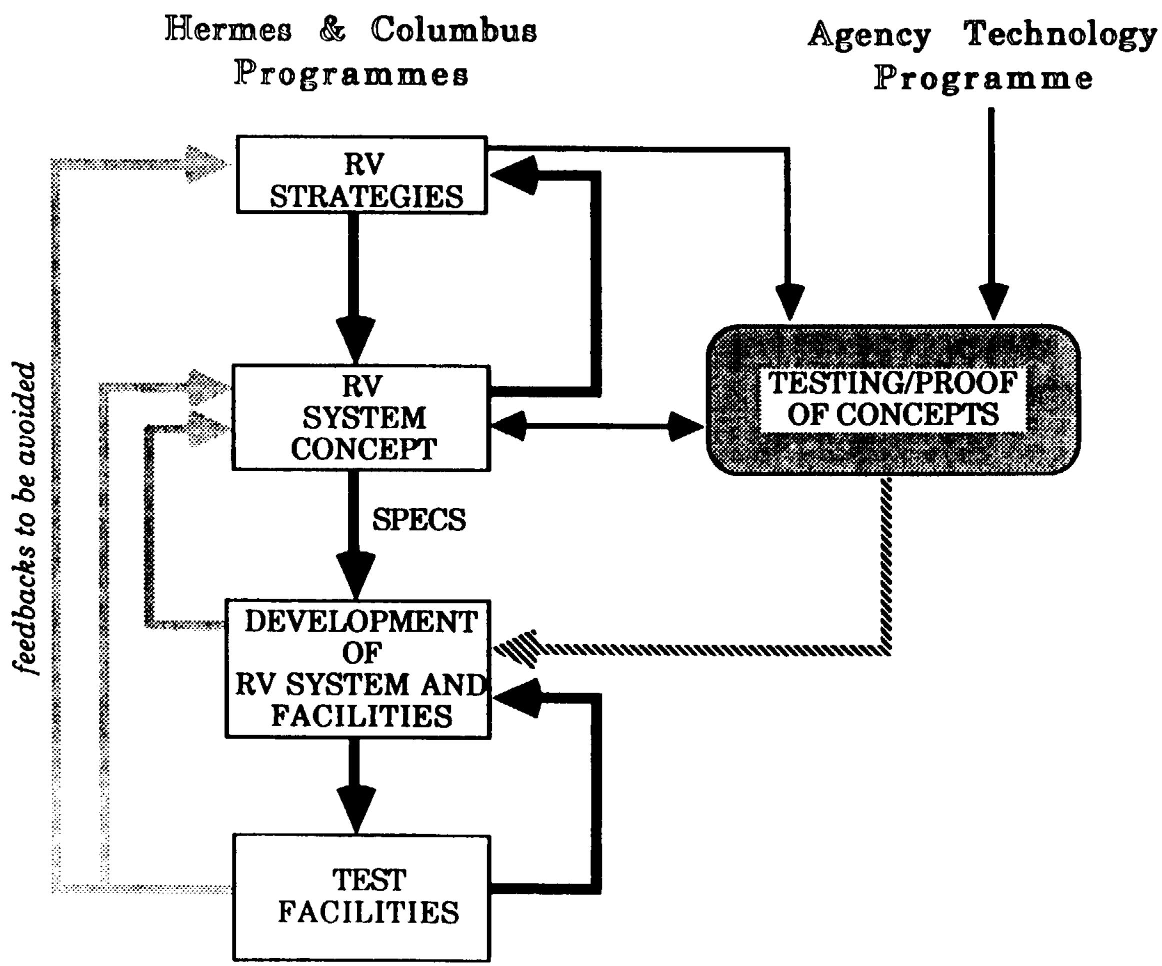
RVD System Proof-Of-Concept in Europe

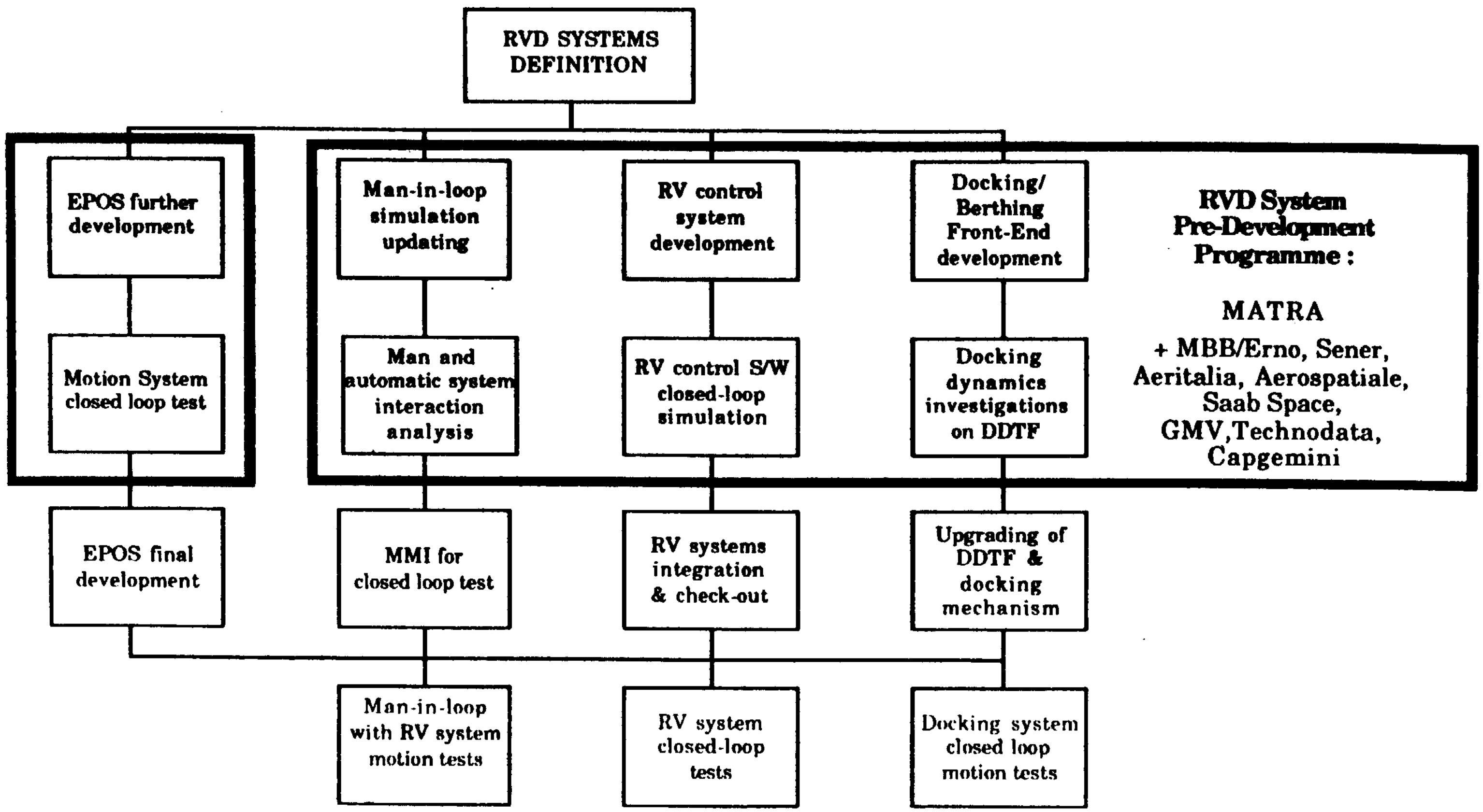
- ➔ Hermes and Columbus programmes necessitate design/development of RV system
- ➔ Numerous studies performed by European Space Agency (ESA) on RV and proxops
- ➔ Necessity to synchronize RV-related projects activity to avoid mis-design of RV system
- ➔ A RV System Proof-Of-Concept programme has been initiated by ESA
- ➔ Assessment of Hermes and Columbus Requirements and Baselines
- ➔ Setup of RV System including projects commonalities, and extended to mission/spacecraft alternatives (AR5/MIR, scenarios, equipments,...)
- ➔ Utilization of material available in Europe:
  - hardware and software developed under ESA contracts
  - test facilities developed in France (Docking Dynamics Test Facility, CNES/MATRA) and in FRG (European Proximity Operations Simulator, ESA/DLR)

RVD System Proof-Of-Concept in Europe

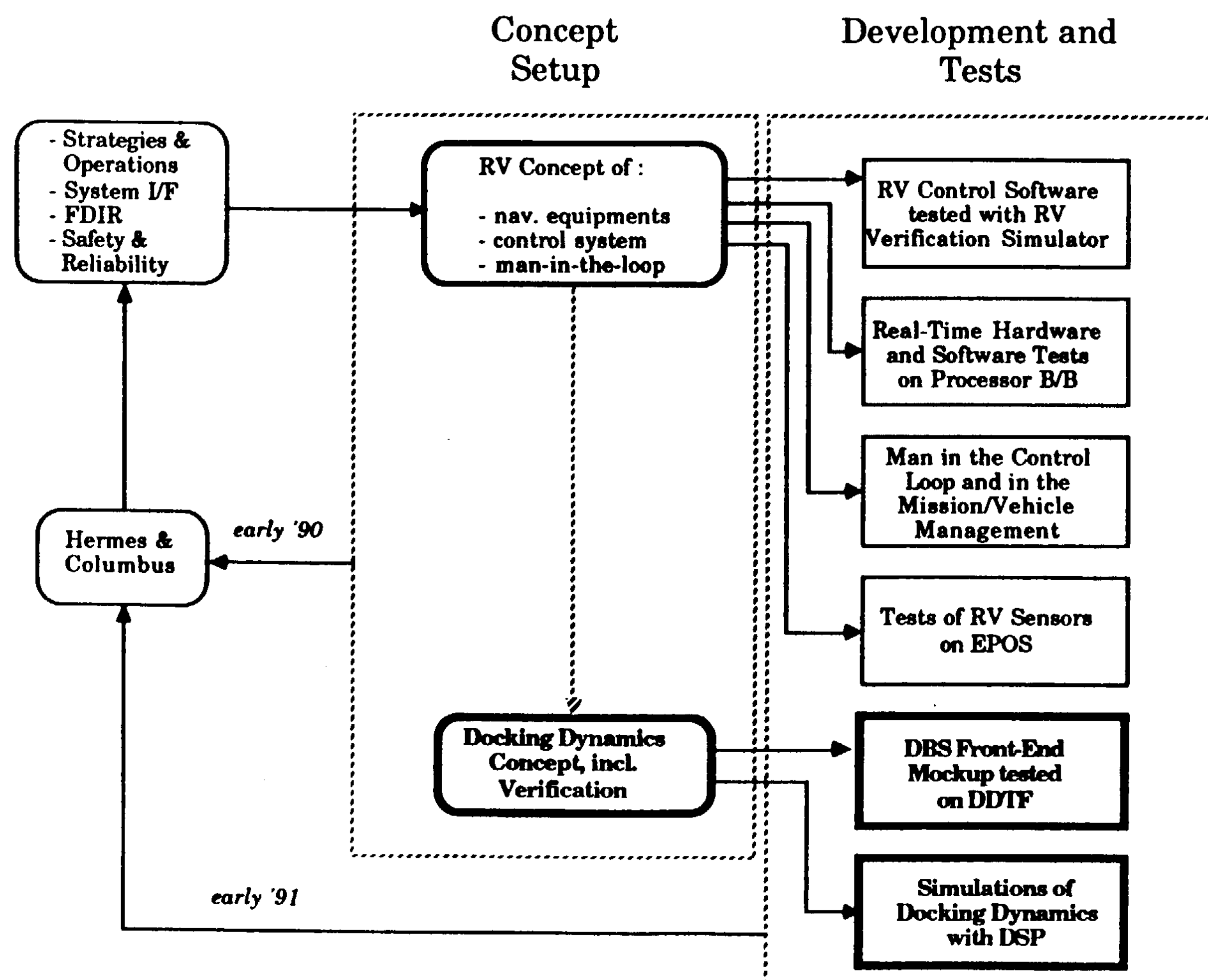


RVD System Proof-Of-Concept in Europe

SCOPE OF PROGRAMME FOR A COMPLETE PROOF-OF-CONCEPT FOR RVD



Docking Dynamics within European RV System Pre-Development Programme

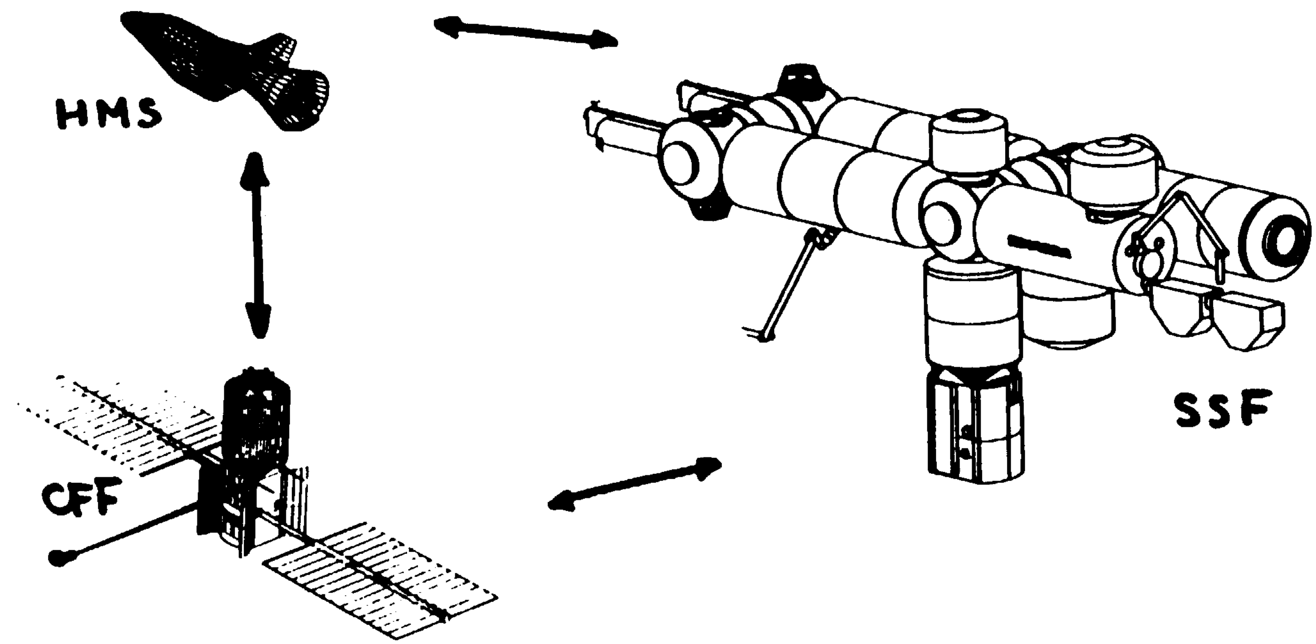


Assumed Contact Conditions

	Berthing With Freedom (1)	Worst case Hermes Docking
Axial Velocity (m/s)	0.049	0.03
Lateral Velocity (m/s)	0.046	0.02
Lateral Misalignment (m)	0.077	0.05
Roll Angular Rate Error(°/s)	0.52	0.20
Yaw/Pitch Angular Rate Error (°/s)	0.20	0.20
Roll Angular Error (°)	1.50	1.50
Yaw/Pitch Angular Error (°)	1.50	1.50

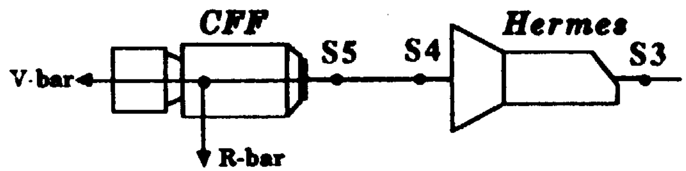
(1) : runaway of one joint of manipulator

Scenarios of interest



- For the reference mission to Freedom, Hermes shall be fitted with a passive D/B interface half that allows mating by berthing to ports fitted with an active half of Freedom, i.e. same ports as those used by CFF
- Docking interfaces of CFF and Hermes shall be compatible with each other and with the SSF docking interface

Typical Approach Scenario for Docking Operations

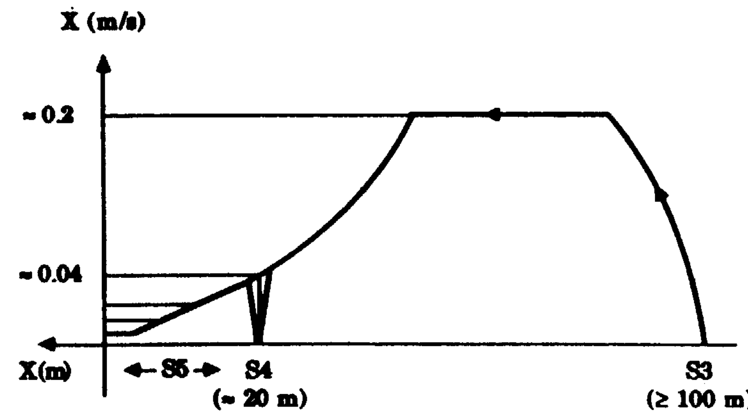


S3 —> S4
SRS (R, LOS)
Star Sensor
LL-RCS (bi-liquid)

S4 —> S5
SRS (R, LOS, rel. att.)
LL-RCS (cold gas)

S5 —> contact
SRS (R, LOS, rel. att.)
no actuation (free drift)

S3: hold point
S4: optional hold point + switch to cold gas
S5: AOCS switch-off



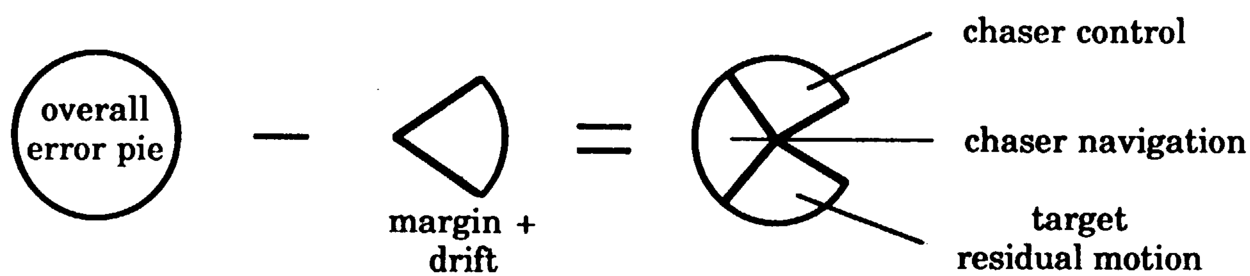
Typical Relative Velocity Profile

GNC/DBS Performance Allocation for Sizing of Docking/Berthing System

→ errors allowed at meeting point (manipulator capabilities, tolerances of docking interfaces) must cope with residual misalignments/rates at end of proximity operations

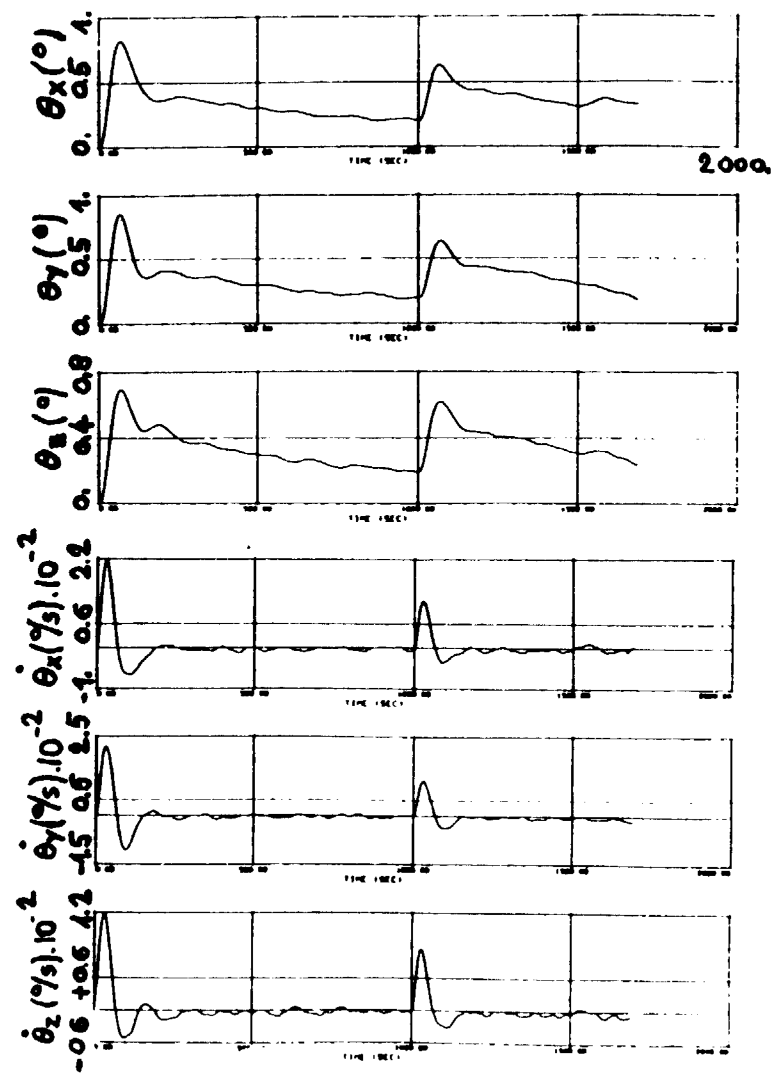
→ these errors determine:

- how the chaser must reach the target
- how target can be allowed to wait the approaching chaser



GNC/DBS Performance Allocation for Sizing of Docking/Berthing System (cont'd)

	2D cov. tool			3D cov. tool	
	CS	PS	TGT	CS	PS
θ_x (deg)	-	-	-	0.3	8.4e-2
θ_y (deg)	0.25	0.02	0.51	0.2	4.6e-2
θ_z (deg)	-	-	-	0.2	8.6e-2
Ω_x (deg/s)	-	-	-	0.05	1.3e-3
Ω_y (deg/s)	1.5e-3	6.e-4	2.e-4	0.03	1.4e-3
Ω_z (deg/s)	-	-	-	0.02	2.3e-3
Y (mm)	-	-	-	5.5	8.8
Z (mm)	5.	3.5	6.6	9.	6.1
$\dot{X}$ (mm/s)	0.3	0.2	0.3	0.2	0.2
$\dot{Y}$ (mm/s)	-	-	-	0.2	0.2
$\dot{Z}$ (mm/s)	0.3	0.3	0.3	0.35	0.25

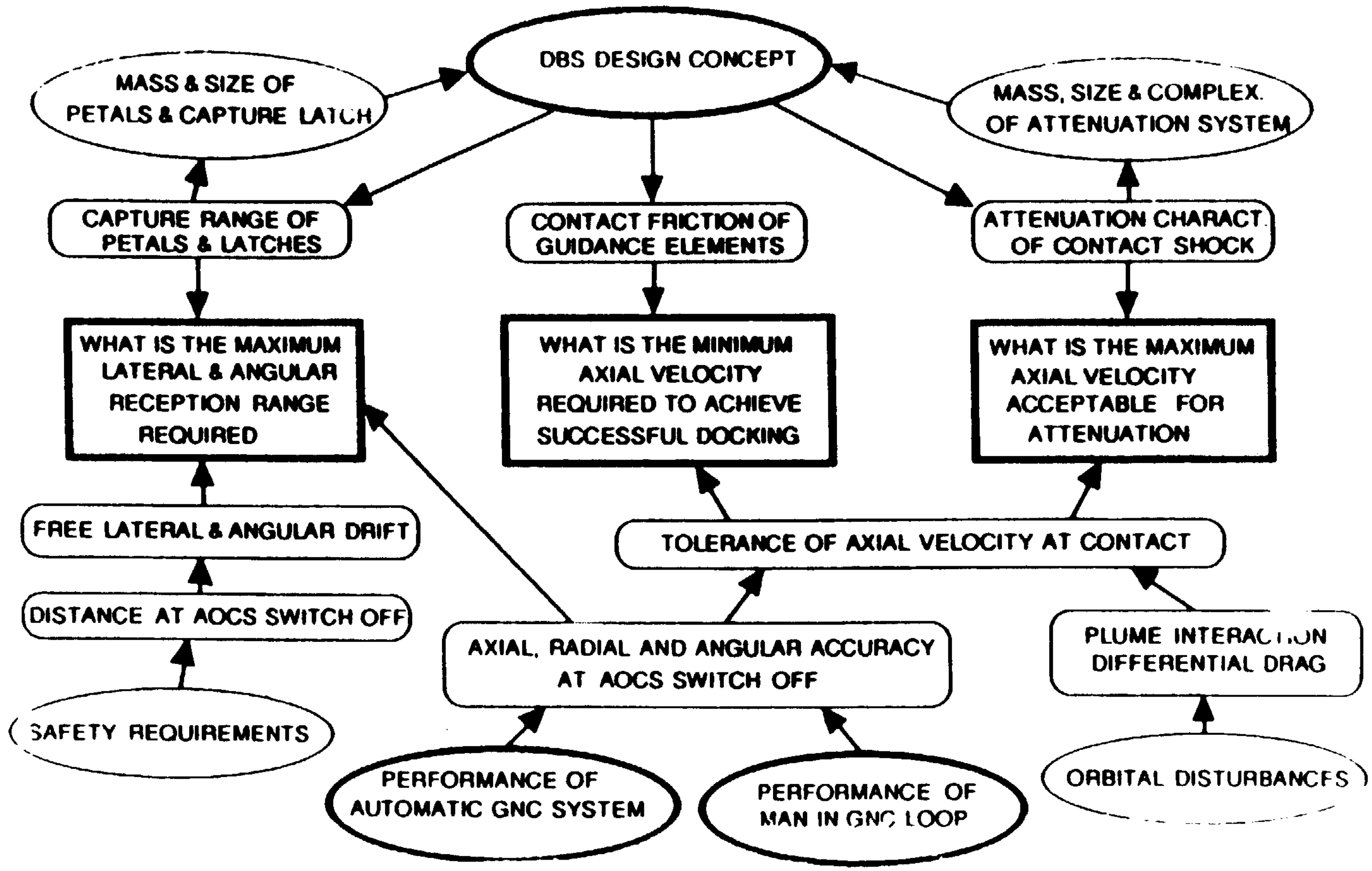


GNC/DBS Performance Allocation for Sizing of Docking/Berthing System (cont'd)

- ➜ a Docking/Berthing System cannot be designed and dimensionned independently from the design of the chaser Guidance, Navigation and Control system, and vice-versa
- ➜ compromise is needed between requirements on GNC (sensor, estimation, control) and on DBS

Residual Misalignments				Residual rates			
small		large		small		large	
+	small docking interface	-	bigger docking interface	+	low attenuation requirements (passive attenuation	-	increased attenuation needs (heavier docking interface)
-	accurate chaser GNC	+	relaxed chaser GNC requirements (sensor bias)	-	increased requirements on GNC • low sensor bias • low GNC band-width	+	relaxed requirements on chaser GNC
-	small bias sensor	+	relaxed target waiting conditions	-	demanding target waiting conditions	+	target waiting conditions relaxed
-	restricted target waiting conditions						

Design Compatibility of GNC and Docking/Berthing Systems



Specification for DBS Concept

➔ Best range for axial velocity: $5 \text{ mm/s} \rightarrow 30 \text{ mm/s}$

Compatible with:

- Maximum axial loads on spacecraft
- GNC requirements for acceptable kinematical conditions at contact:
    * lateral and angular misalignements
    * residual velocities

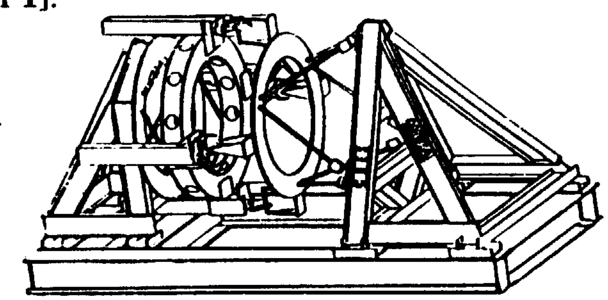
➔ DBS concept selected by dedicated analyses needs to be assessed by <u>verification tests</u> for parameter optimisation (orientation of petals, stiffness/damping factor of attenuation system, capture latch strategy, surface characteristics, ...)

➔ The verification activity due to consolidate the present DBS FE design, and to refine allocation between DBS Front-End capabilities and GNC requirements

Software and Hardware Tools for Verification of DBS Front-End Design

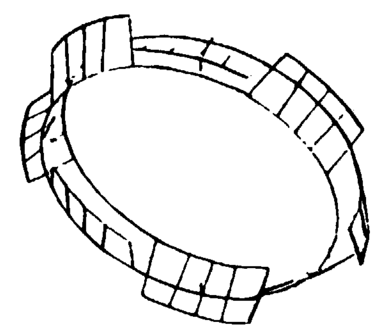
→ Docking Dynamics Test Facility [Ref 2], on which a scaled down DBS FE mock-up developed by SENER will be mounted [Ref 1]:

- an active loop based on a 6-axis force/torque detection
- mathematical models of spacecraft orbital motion and attitude dynamics
- a 6 DOF's servo motion



→ Docking Simulation Programme (DSP) allowing a modellization of the DBS Front-End mock-up and of its possible extensions:

- DSP allows 3D simulations of the impact dynamics for complex DBS
- DSP includes newtonian model for impact simulation
- Normal contact forces are modelled by $F = K.\alpha^n + C.\dot{\alpha}^m$



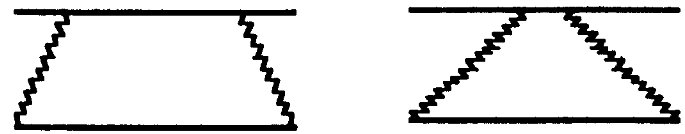
Verification of DBS Front-End Design

	DDTF + DBS FE mock-up	DSP + DBS FE model
Advantages	• real mechanism is tested • very good representativity of contact forces	• high flexibility for design changes implementation • low kinematical/dynamical limitations • 0 g environment
Drawbacks	• 1g environment • kinematical/dynamical limitations	• modellization errors for: - representativity for non linear effects - contact forces

Verification of DBS Front-End Design (cont'd)

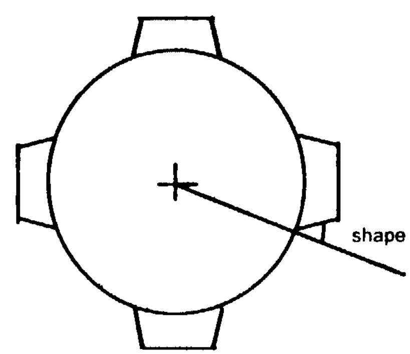
➜ DBS FE mock-up provides various:

- attenuation stage characteristics :
  - four sets of stiffness
  - tunable damping coefficient
  - different possible ratios between axial, lateral and rotational stiffnesses



- guiding petals characteristics:
  - 3 or 4 petals
  - orientation (external or internal)
  - inclination
  - shape

- capture latches implementation points:
  - on the fixed part
  - on the attenuation ring
- capture latches actuation velocities



Expected Outputs of Verification Tests for DBS Front-End Mockup

➔ On Docking Dynamics:

Thanks to a sensitivity analysis on the several parameters, insight in the interrrelations in a 3D frame analysis between:

- attenuation stage characteristics
- guiding petals characteristics
- capture strategy
- masses and inertia of the involved S/C

and their consequences on:

- capture success
- attenuation stage stroke
- loads on the spacecraft

➔ On Verification tools:

Identification of necessary improvements on DDTF and on DSP for future applications, via cross-correlation runs and tests on DSP and DDTF

Docking Dynamics Analysis

→ References

1 J.J. Gonzalez-Vallejo (1990)
Docking Mechanisms : Some European Development Programmes
Autonomous RVD Conference, Houston (USA)

2 M. Le Du (1990)
Overview of CNES Rendezvous and Docking Activities
Autonomous RVD Conference, Houston (USA)

Activities reported in this presentation have been performed in the frame of the Technology Programme of the European Space Agency

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CONTENTS

1. THE RENDEZVOUS SCOPE RELATED TO THE HERMES MISSION

2. ALGORITHMS AND TOOLS OF VALIDATION OF THE STRATEGIES

3. SPECIFIC RVD SENSORS

4. RVD HARDWARE VERIFICATION

5. PROSPECTIVE SUBJECT : EXPERT SYSTEM FOR RVD OPERATOR ASSISTANCE

ORBITAL FLIGHT PROFILE

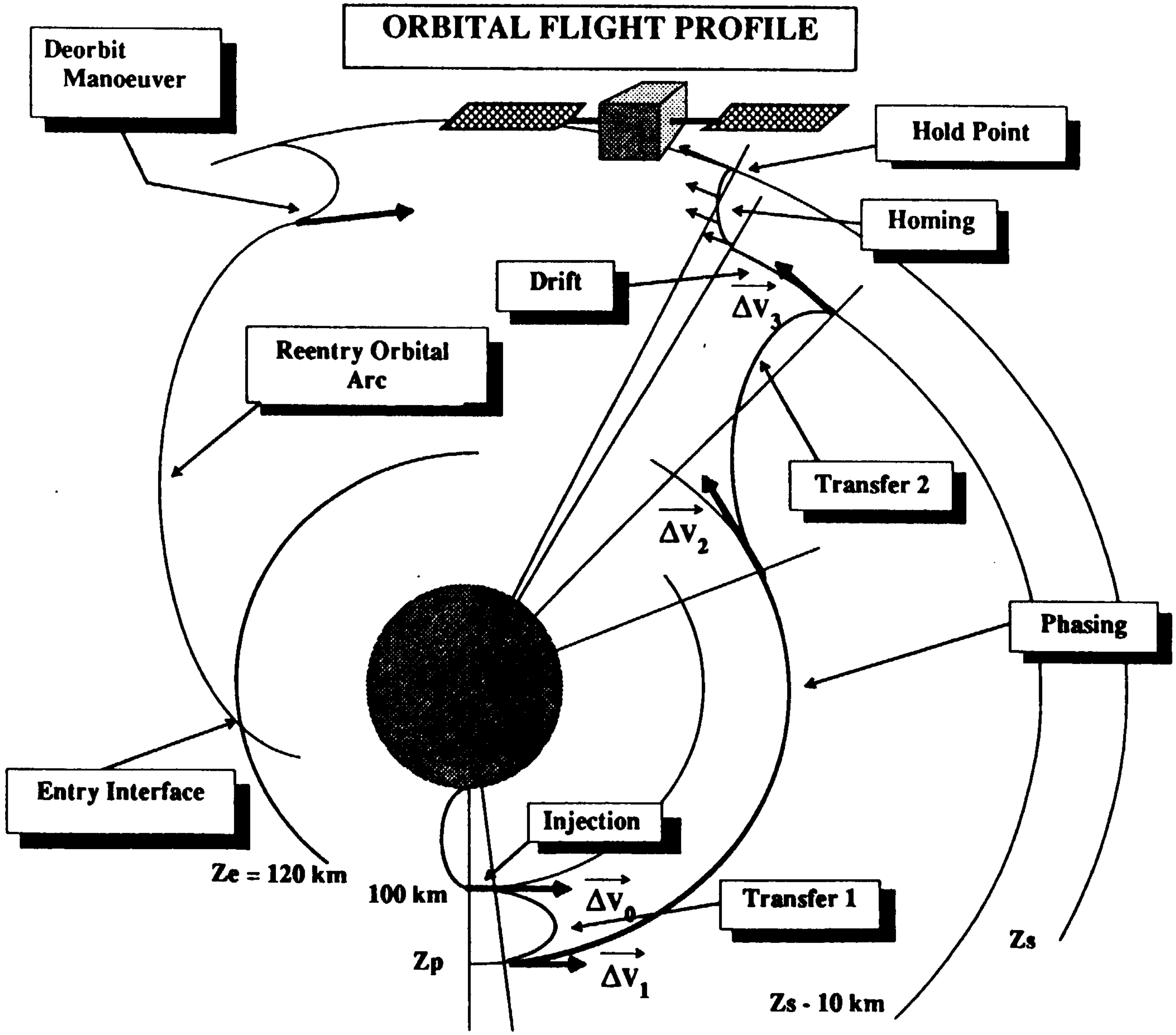
The HERMES mission can be decomposed in 6 main phases which are the launch, phasing, rendezvous, servicing with the station, separation and reentry.

The timeline has to consider

◊ the crew activities periods

◊ the necessity of performing the last meters during the orbital day.

ORBITAL FLIGHT PROFILE



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GENERAL ASPECTS AND REQUIREMENTS

→ CREW SAFETY REQUIREMENTS :
- collision avoidance and safe separation
- the mission is designed on FO/FS criteria

→ SUCCESS OF THE RENDEZVOUS :
- accuracy requirement
- optimisation in term of propellant consumption

→ AUTOMATIC FLIGHT:
- RVD strategy and operations timeline must be pre-programmed

→ ROLE OF THE "MAN IN THE LOOP":
- supervisor of the situation
- capability of piloting the vehicle in cases of contengencies

ALGORITHMS AND TOOLS OF VALIDATION

The in-orbit part of the RV mission bertween HERMES and MTFF (Man Tended Free Flyer) space station can be divided into three phases : Phasing, Homing/Initial approach and final approach.The validation of the strategies consists in tools simulation with the caracteristics shown in the vu-graph.

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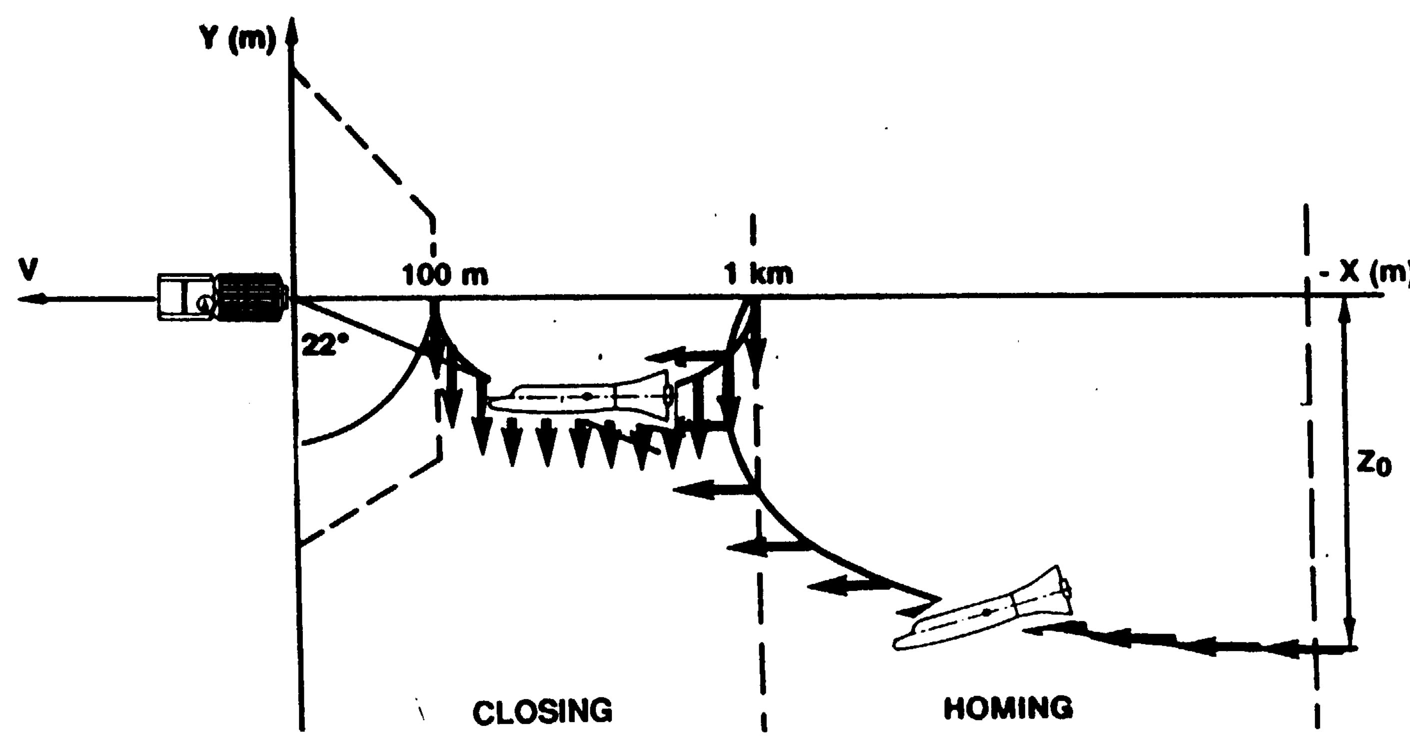
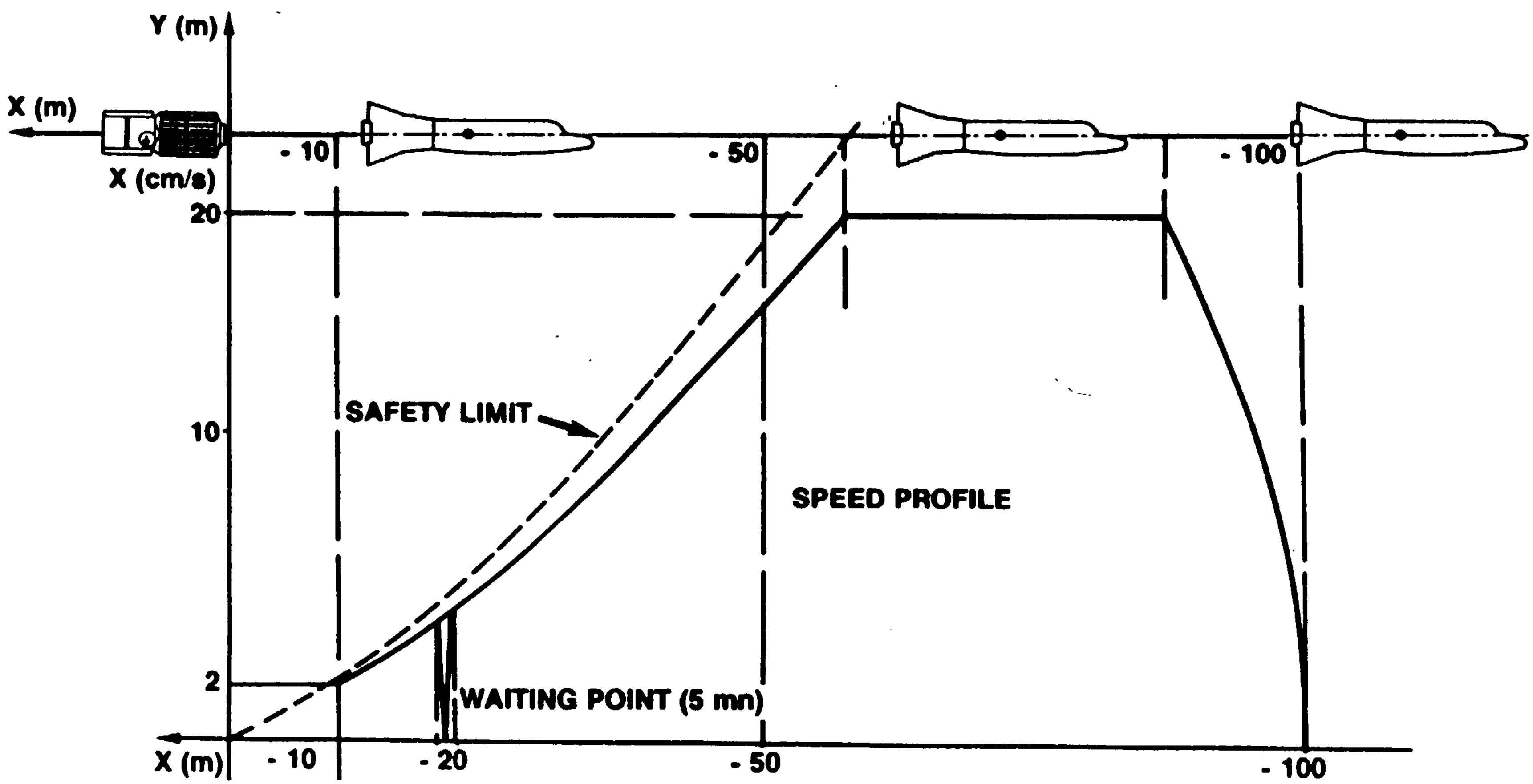
HERMES/MTFF HOMING AND CLOSING N BOOSTS STRATEGIES



HERMES/MTFF FINAL APPROACH 100m → 0m



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TOOLS OF VALIDATION SIMULATION

HOMING – CLOSING

* RELATIVE ORBITAL DYNAMICS MODEL
* PERTURBATION : DIFFERENTIAL J2, DIFFERENTIAL AIR DRAG
* RELATIVE NAVIGATION MODEL USING GPS
* TRAJECTORY GUIDANCE/CONTROL
  - INTERACTION WITH ATTITUDE CONTROL

(developped by CNES/MATRA)

FINAL APPROACH

* CLOHESSY WILSHIRE MODEL
* PERTURBATION : DIFFERENTIAL AIR DRAG, PLUME EFFECT, SLOSHING, FLEXIBLE MODES
* NAVIGATION BY RVD SENSOR
* 6 DOF GUIDANCE/CONTROL (DIGITAL AUTOPILOT)
* PILOT INTERFACE (FOR MANUAL APPROACH)

(developped by CNES)

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RENDEZ VOUS SENSOR

1. IMAGING SENSOR DEVELOPPED BY MATRA

2. PHASE MEASUREMENT TELEMETER SENSOR DEVELOPPED BY SERCEL

RVD SPECIFIC SENSORS

These sensors have been developped for proximity operations. The main requirements for RVD sensor are the capability of measurement in perturbated environment (especialy with sun light in the field of view) and without any mechanism (to improve the fiability).

1. IMAGING SENSOR

The originality of this sensor is the FDT (Flash During Transfert) mode which consists in a high frequency transfert (> 1MHZ) of the lines of the CCD matrix.

◊ continuous light appears on the CCD as a column which is easy to filter

◊ need of a higher pulsed laser diode frequency than the transfert frequency to obtain a clear image on a single line.

◊ barycenter calculation allows a good accuracy.

To perform measurements from 100m to contact with a single RVD sensor several patterns are used during the approach, and a 3 dimensional one is necessary to perform the attitude maesurement in the last meters.

2. PHASE MEASUREMENT TELEMETER SENSOR

The modulated signal emitted by a high power laser diode is reflected by a retroreflector placed on the target . The range is calculated from the phase difference between the received and the reference signal. The light of sight measurement is performed through a barycenter calculation, which allows a good precision due to the 4 dials diode used in the receptor.

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IMAGING SENSOR CONCEPT

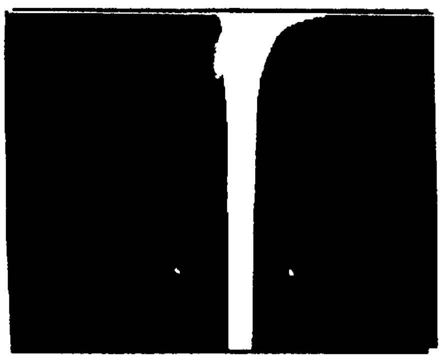
- The same sensor is able to perform relative measurement (position and attitude) from the medium range to the proximity (200-0m), without mechanism (to improve the fiability) and with the sun in the field of view.

- the rendezvous sensor hardware and basic concept are derived from star tracker technology based on CCD detection, with an active illumination by pulsed laser diode .

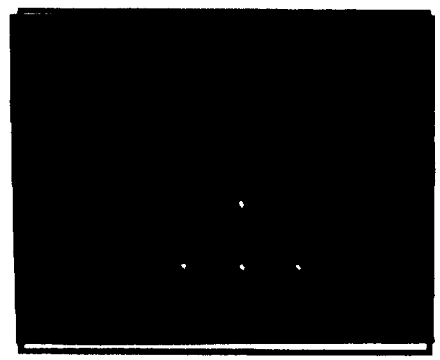
- Use of the FDT (Flash During Transfert) mode (patented by MATRA) to reject parasitic sun illumination .

IMAGING SENSOR
FDT MODE

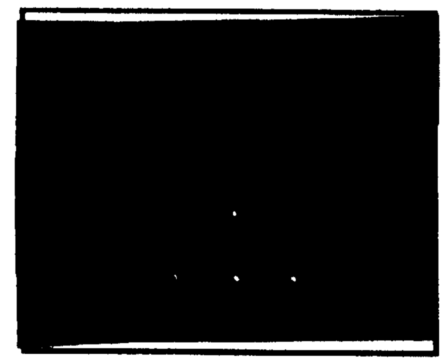
MATRA PATENT



Normal mode
with integration
:saturation of
the CCD with
the sun



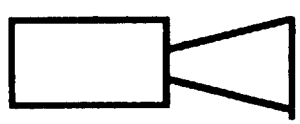
FDT mode before
the substraction
of the sun effect



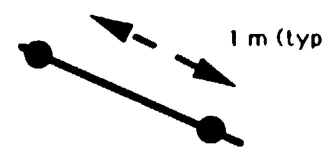
FDT mode after
the substraction
of the sun

IMAGING SENSOR MODULARITY

- medium range (200m - 10m)

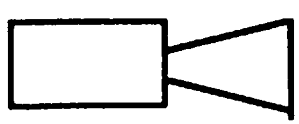


target with 2 points

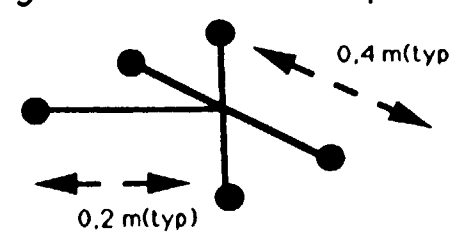


range,
los

- short range (20m - 0m)



target with 3 or 5 points



range,
los,
relative attitude

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IMAGING SENSOR PERFORMANCES (3σ)

parameter	medium range (200-20m)	short range (20-0m)
field of view	10° x 13°	10° x 13°
line of sight accuracy	< 0.05°	< 0.05°
range $\Delta R/R$	< 1%	< 1%
relative attitude accuracy	--	< 0.5° (20 m) 0.1° (1m)
frequency measurement	1HZ	8HZ

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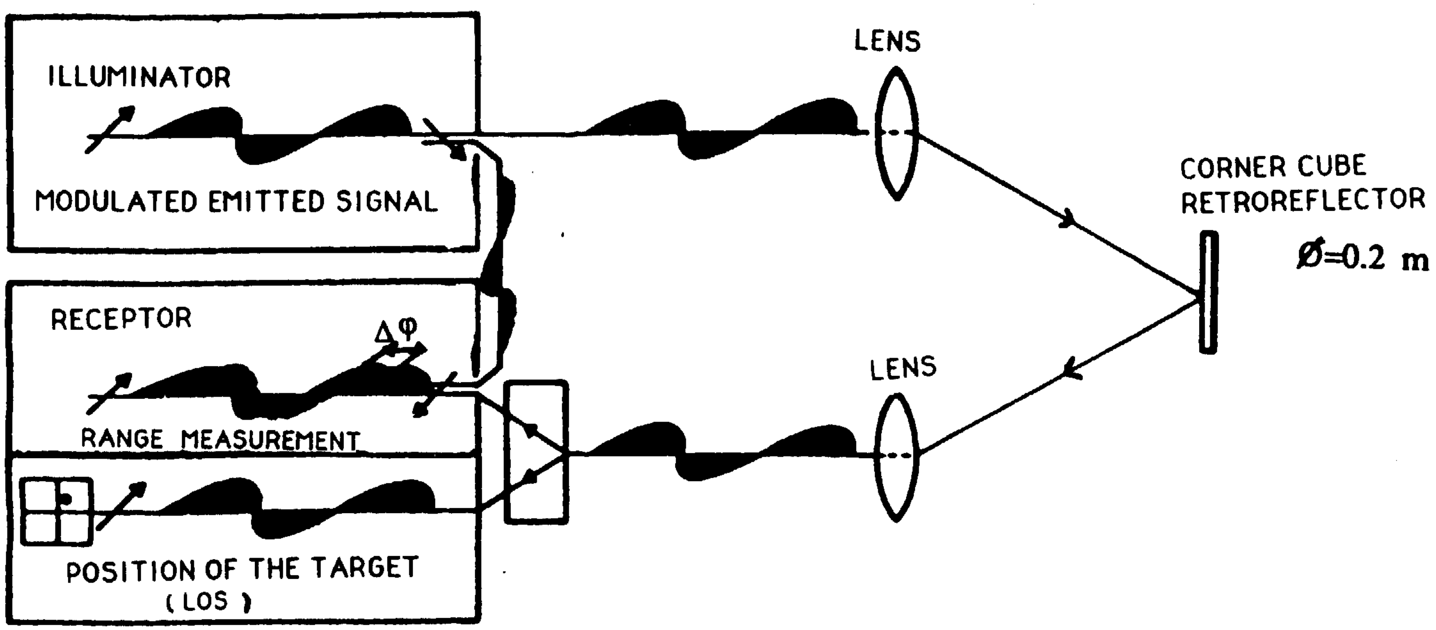
PHASE MEASUREMENT TELEMETER SENSOR PERFORMANCES (3σ)

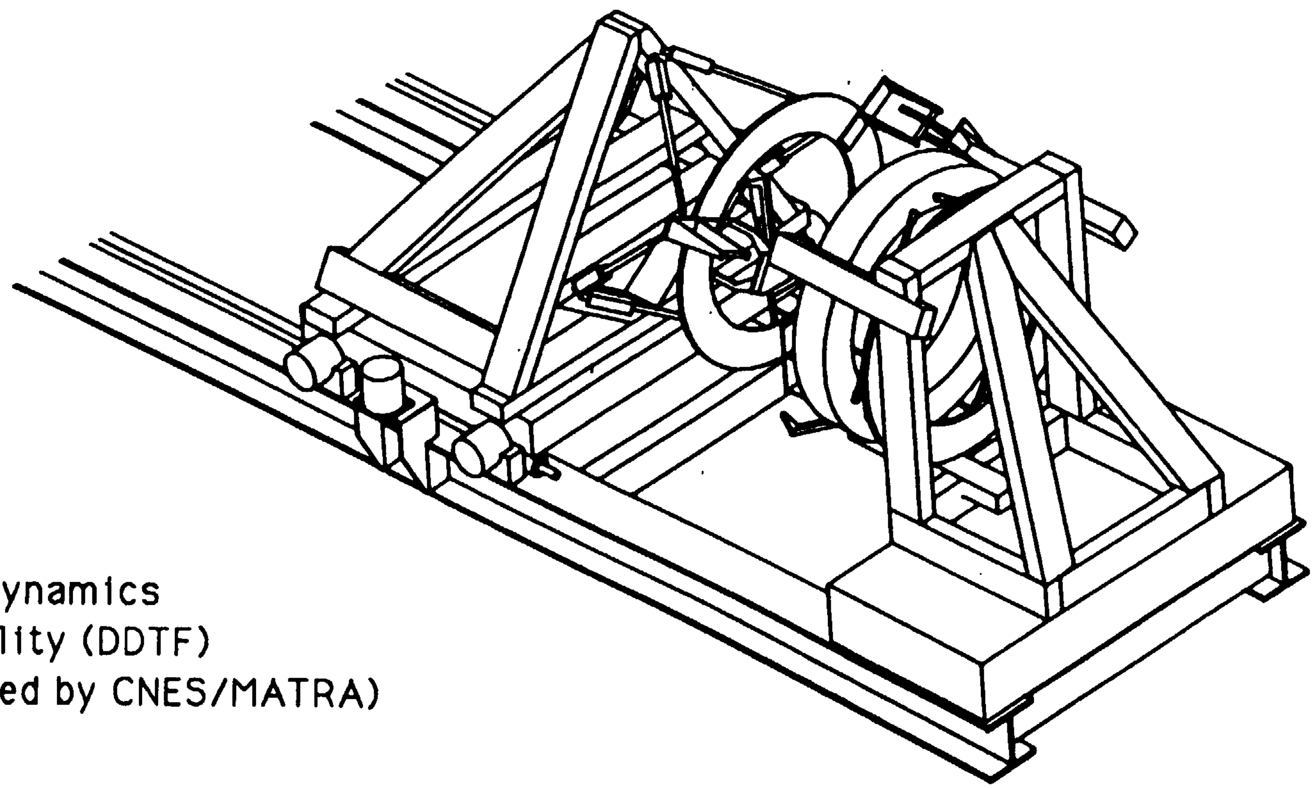
parameter	long and medium range (500-10m)
field of view	10° x 10°
line of sight accuracy	0.05°
range $\Delta R/R$	1%
velocity $\Delta V/V$	10%
frequency measurement	range at 10HZ velocity at 1HZ

PHASE MEASUREMENT TELEMETER SENSOR CONCEPT

→ the phase measurement telemeter sensor is able to perform the relative measurement (position and velocity) without any scanning mechanism and with the sun in the field of view.



RVD HARDWARE VERIFICATION



Docking Dynamics
Test Facility (DDTF)
(developped by CNES/MATRA)

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DDTF ORIGINALITY AND CONTRIBUTIONS

DDTF COMBINES BOTH

<u>1. CONTACT DYNAMICS SIMULATIONS</u>

- DOCKING HARDWARE VERIFICATION WITH LARGE REPRESENTATIVITY

  of vehicule dynamics (inertias, masses, flexibilities, sloshing...)

  of vehicule geometry (COM, axes positioning ...)

  of realistic kinematic conditions prior to docking
  (velocities, position/attitude errors from control)

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2. LAST METERS OF APPROACH KINEMATICS SIMULATION

→ IMAGING SENSOR CLOSED-LOOP DYNAMIC TESTS

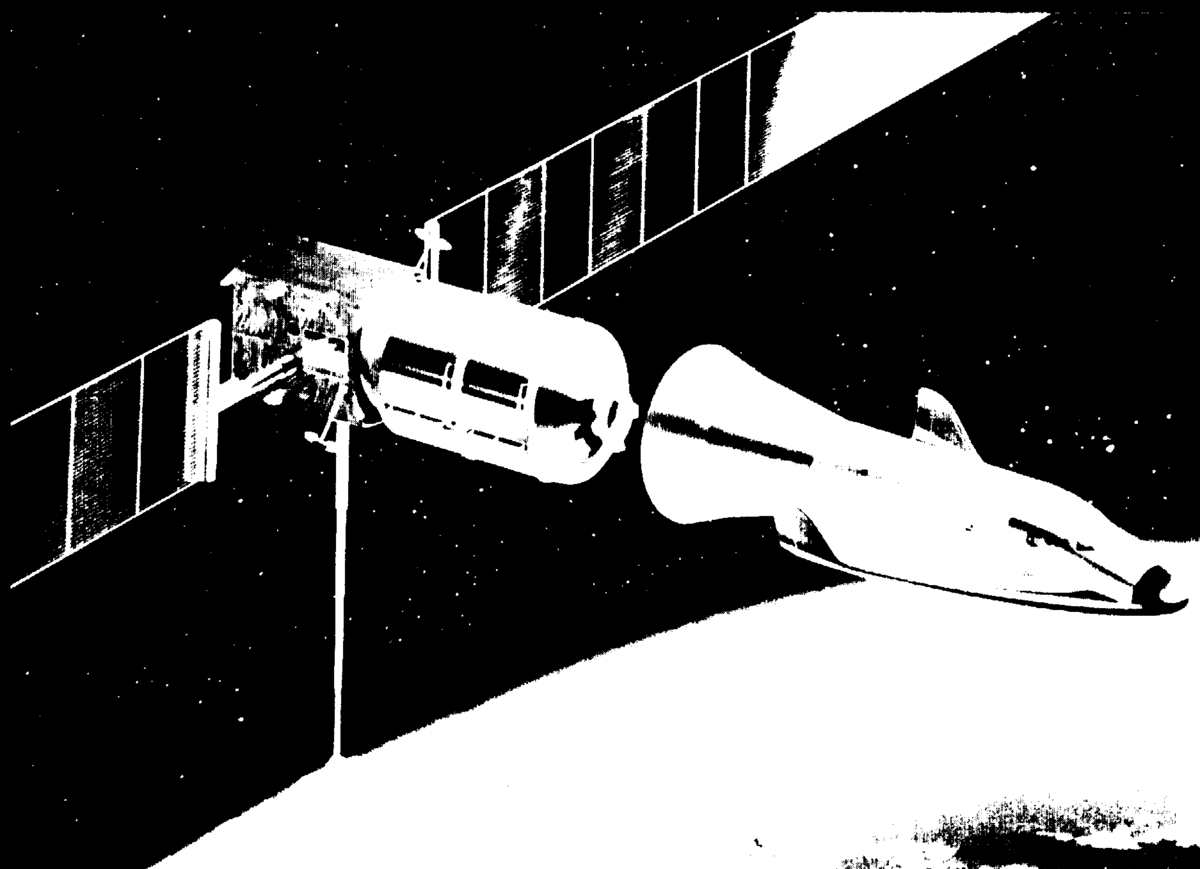
with control algorithms and equipement model
(thrusters,gyros ...)
environment effects simulation
(plume impingement, differential drag ...)

sun light conditions (target mock-up, sun illuminator)

→ MAN IN THE LOOP ANALYSES

with video feedback
simplified man/machine interface

overview of CNES rendezvous and docking activities



AUTONOMOUS
RENDEZVOUS &
DOCKING CONFERENCE
NASA - JSC
august 15-16, 1990

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SPECIFIC TECHNICAL FEATURES

DDTF MAKES COMPATIBLE CONFLICTING DESIGN REQUIREMENTS FOR DOCKING TESTS AND PROXIMITY SENSOR/CONTROL TESTS

parameter	docking tests	proximity tests
kinematic range	20 cm 1mm/s- 2cm/s	5m 1mm/s-10cm/s
structural stiffness	high	medium
	(hardlocking by air brakes)	
bandwith	6HZ	1HZ
gravity compensation	yes (shocks phasis)	no

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PROSPECTIVE SUBJECT

EXPERT SYSTEM FOR RVD OPERATOR ASSISTANCE

developped by CNES/MATRA

EXPERT SYSTEM

1. INTRODUCTION

To improve the reliability and safety of the HERMES space plane, one must take advantage of both man and machine that are on board and ensure that they cooperate well;

The automatic system with the failure detection isolation (FDI) is highly dependant to detection threshold, and then subject to problems such as false alarms or inability to detect and/or isolate a failure.

The expert system can ensure a larger autonomy of the space plane in case of link interruption between the control center and the vehicle.

The operator is dedicated to high level tasks , so decision support facilities are needed.

2. ARCHITECTURE OF THE EXPERT SYSTEM

The general architecture of the system is shown on the vu-graph. The expert system is composed of two modules corresponding to the main functionalities : a diagnostic and situation assessment module and a replanning module which have been implemented and experimented.

The diagnostic module :

consists on a hierarchy of functional schemes describing at successive levels of details:

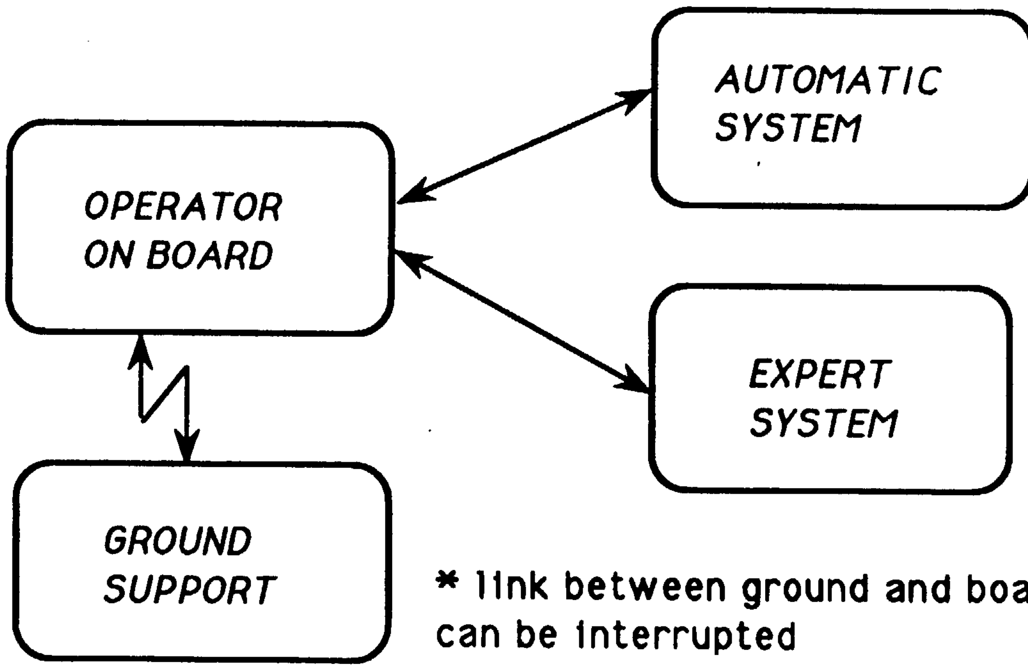
◊ the functional elements of the system (functions, equipements...)
◊ the functional links between them
◊ the observable parameters associated to some parts of the scheme .

The mission replaning module :

As the vehicle is out of his nominal profile or with equipement failures, this module propose from a given initial situation the best strategy through a class of trajectory (hohmann or elliptic transfert, standby) considering security constraints, consumption,timeline.

The perspective for 1992 is to build an integrated test bed where the assistant is connected to real time simulators. this will permit evaluation of the oprational interest of the system in realistic conditions and could also be used for other activities such as training of operators throughout a simulated Rendezvous mission.

ENVIRONMENT OF THE EXPERT SYSTEM



* synthesis of the mission and vehicle situation
* capability to resolve problems

* rigid strategies

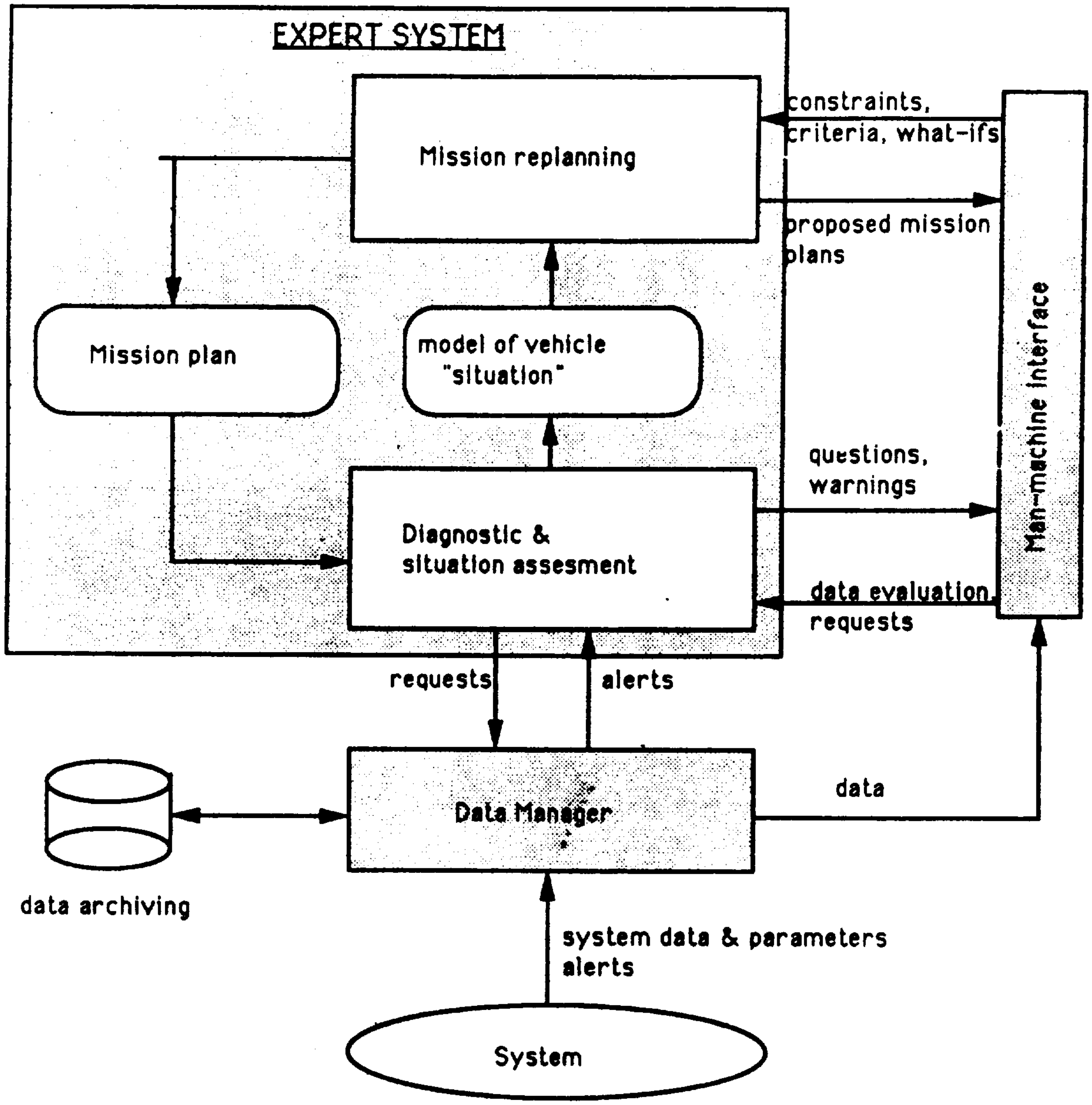
* capability to give explanations to the pilot
* complementary of the automatic FDIR for non-straghtforward anomalies

* link between ground and board can be interrupted

THE FUNCTION OF THE EXPERT SYSTEM CONSIST IN PROVIDING A HELP FOR DECISION :

- GIVING EXPLANATIONS
- MANAGING THE COMPLEXITY OF THE SITUATION ASSESSMENT

<u>THE PILOT HAS ALWAYS THE FINAL RESPONSABILITY</u>



ON-BOARD SYSTEM FUNCTIONALITIES
AND ARCHITECTURE

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CONCLUSIONS

→ CURRENT <u>RVD TECHNOLOGY RESEARCH</u> FOR USE IN HERMES AND COLUMBUS PROGRAMS

→ WORK COORDINATED AT ESA LEVEL

→ CNES FOCUS ON THE HERMES RELATED ISSUES

- ◇ VAST ARRAY OF TECHNICAL CONCERNS
  - APPROACH GUIDANCE TECHNIQUES (FUEL EFFICIENT AND SAFE)
  - MAN IN THE LOOP VERSUS AUTONOMOUS PROXIMITY OERATIONS
  - SOFT DOCKING AND MECHANICAL INTERFACE DESIGN
  - CONTROL SYSTEM (ROTATION AND TRANSLATION COUPLING)
  - ON-BOARD SENSORS
  - VERIFICATION TOOLS (DOCKING TEST FACILITY AND GNC SIMULATORS)
- ◇ MAJOR IMPLICATION OF MATRA AS INDUSTRIAL PARTNER IN FRENCH INDUSTRY
- ◇ GROUND DEMONSTRATION AND VALIDATION OF AUTONOMOUS RVD FOR HERMES USING ON-GOING TECHNOLOGY DEVELOPMENTS WITHIN 3 YEARS

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VIDEO BASED SENSOR FOR AUTONOMOUS DOCKING

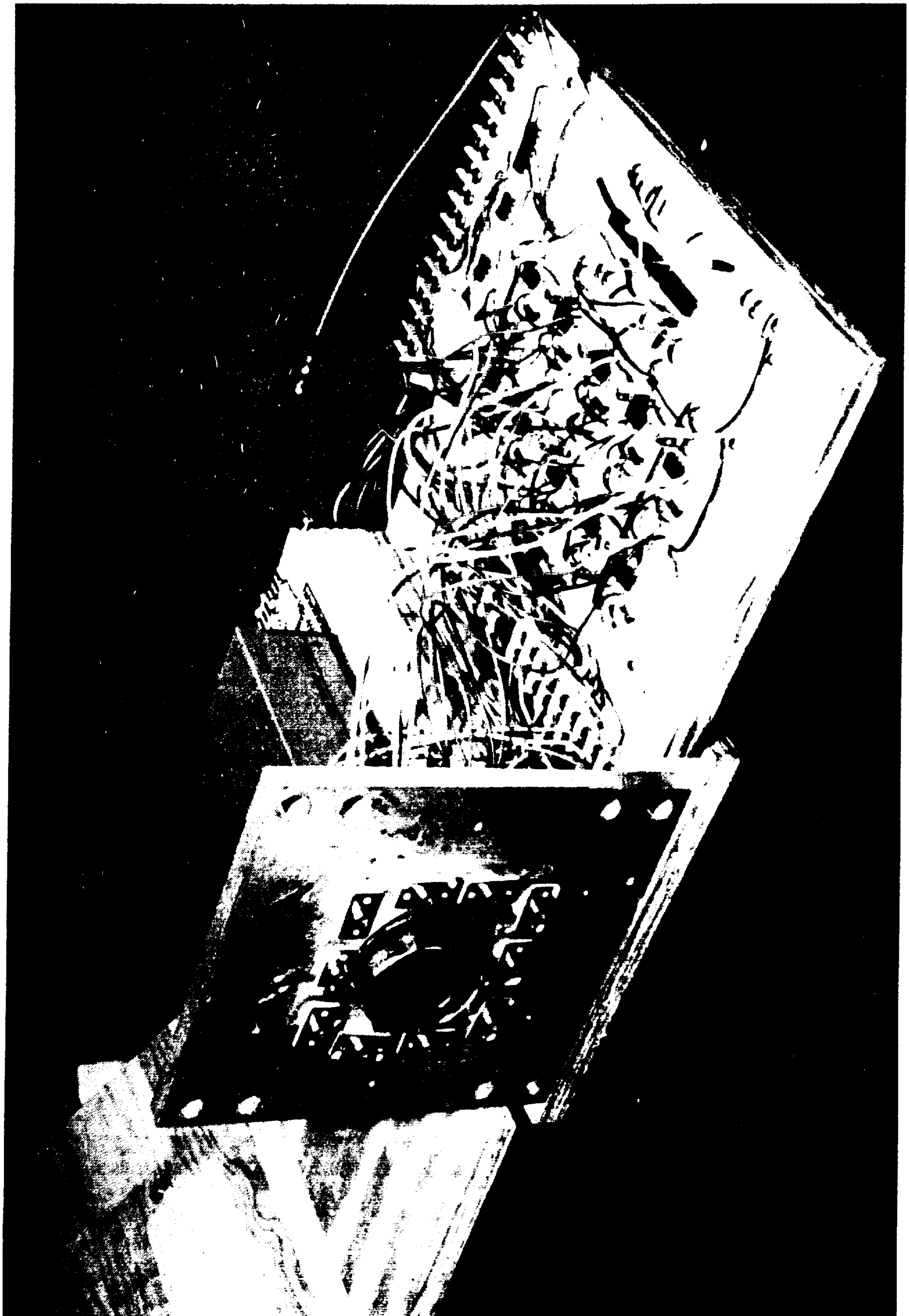
RICHARD T. HOWARD

NASA/JSC AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE
AUGUST 15-16, 1990
HOUSTON, TEXAS

A Video Based Sensor for Autonomous Docking

Work has gone on at Marshall Space Flight Center (MSFC) for approximately three years in the development, testing, and implementation of video based sensors for autonomous docking. The first sensor to be actually implemented in a large-scale vehicle simulation environment was the Retro-reflector Field Tracker (RFT), a Charge Injection Device (CID) based flight experiment sensor from the Solar Array Flight Experiment flown in 1984. The sensor used a single set of laser diodes at 820nm to create reflections from the targets, which consisted of retro-reflective tape, while subtracting out a background picture that reduced the effects of constant sources of light. It would, however, track the light that reflected from anything on the target, so it was not suitable for the noisy environment posed by the multi-layer insulation used on most spacecraft today.

The next video sensor was specifically developed to meet the challenge posed by the multi-layer insulation, as well as the challenge to implement a sensor that would have a minimal impact on both the target and the chase vehicles. A video sensor composed entirely of off-the-shelf components was chosen to be built for its simplicity and low cost. The target chosen was a modified Remote-Manipulator System (RMS) grapple fixture target, so that it would still be usable by the astronauts. This sensor used two sets of laser diodes arranged in a ring around the solid-state Charge-Coupled Device (CCD) based camera. One set of the laser diodes was at 780nm and the other at 830nm, so that there would be a minimum difference between the reflections of the two sets of diodes. See Figure 1 for a photograph of the sensor box containing the CCD camera, lens, laser diodes, laser diode driver circuits, and a power supply. A Data Translation DT2861 real-time frame-grabber and digitizer was chosen for the video acquisition portion of the sensor because it has a large memory capacity and supports several frame manipulation routines in the hardware. A 20MHz Compaq 386 Deskpro processor was chosen to house the frame grabber and perform the necessary control and calculations.



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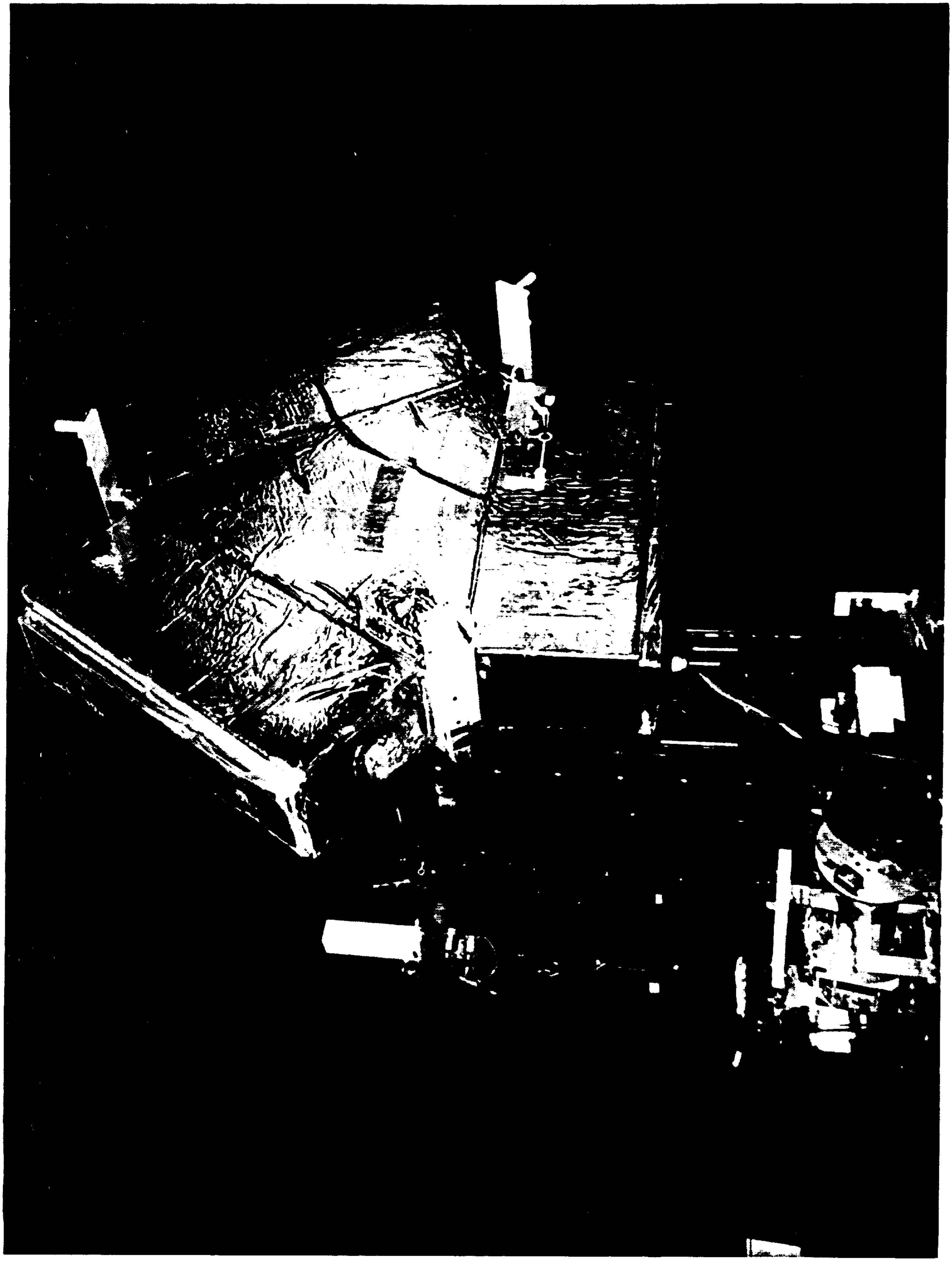
Modified RMS Target for Autonomous Docking

The target consisted of the RMS target with the addition of three circles of retro-reflective tape having narrow bandpass optical filters in front. The filters pass 780nm wavelength light at up to 40 degrees angle of incidence. The target can be seen in Figure 2 on the right side of the satellite simulator.

The satellite simulator is mounted on motors that can move it up and down, pitch it up and down, and roll it clockwise or counterclockwise. The other three degrees of freedom are provided by the air bearings that the satellite simulator sits on, controlled by compressed air thrusters. This vehicle can move in all six degrees-of-freedom, providing a good vehicle for testing autonomous docking.



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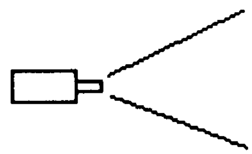
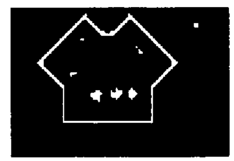
How the sensor works

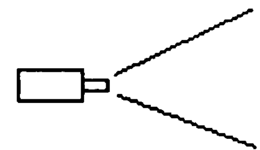
The sensor works by first acquiring the target, using the two sets of laser diodes to get a low noise differential picture. The sensor then matches up the reflections it has spotted to the known parameters of the camera image of the target's retro-reflectors. Once a positive match occurs, the sensor continues to track the target's reflections in a tracking cycle listed in Table 1. In detail, the sensor tracks the target by first illuminating it with the 780nm laser diodes and then digitizing a picture. This picture consists of reflections from the target's retro-reflectors as well as "noise" reflections and background illumination. Then the 780nm diodes go off and the 830nm diodes are turned on in order to digitize a second picture. This picture contains almost exactly the same information as the first picture, except that there are no reflections from the target's reflectors. The second picture is subtracted from the first picture, rendering a low-noise picture of just the three target retro-reflectors. These spots are tracked using a windowing routine, and the centroids of the three spots are found each cycle. From that information, the bearing, range, and attitude of the target is calculated and differentiated over the cycle time to give the various rates. This information can be fed into a guidance algorithm in order to perform automated docking, or it can be used as a data display to assist a man-performed operation. An advantage of using a video-based sensor over many other types of sensors is the fact that the raw video from the sensor may be monitored or used by a human operator to easily provide manned-oversight of the operation and easy intervention in the event of a problem of some kind.



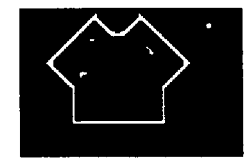
780nm Laser Diodes



1st Digitized Picture

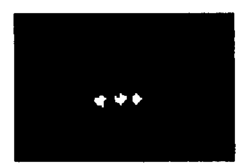


830nm Laser Diodes

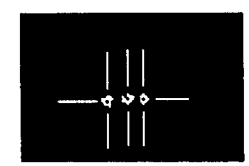


2nd Digitized Picture

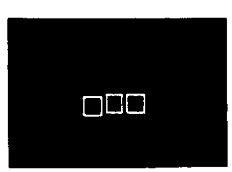
Image 2 subtracted from Image 1



Threshold subtracted from differential image



Centroids found for each spot



Tracking windows established

DISPLACEMENT

X–Y–Z

Roll–Pitch–Yaw

Relative positions and attitudes calculated

Position and attitude information sent to guidance algorithm

Vehicles for Large Scale Autonomous Docking Simulations

This picture shows the vehicles used to do simulated docking at MSFC's Flight Robotics Laboratory. The vehicle on the left floats virtually frictionlessly on air-bearings using compressed air thrusters for propulsion. The OMV mockup on the right is mounted on an eight degree-of-freedom robot arm to allow it to maneuver in the full volume of the facility.

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Sensor Characteristics - Present and Potential

This is a list of some of the current sensor's characteristics as well as the characteristics of the expected next sensor. The update rate is approximately 450 milliseconds at longer ranges, but goes up to 600ms at closer ranges (1/2 meter). The laser diodes were positioned to cover a 30 x 30 degree solid angle, but at the nearer ranges work out to 40 x 40 degrees. The maximum pitch and yaw attitudes are 40 degrees due to the filter being used. A broader-bandpass filter could increase that but would also increase the susceptibility to noise and solar interference. A specially designed retro-reflector and filter could also increase the maximum attitudes, but the center post reflector effectively limits the sensor to being able to see a maximum yaw of 60 degrees, so a special target would not return much for the trouble.

Many potential improvements have been identified, but most of them have drawbacks, so the final choice of a specific system would depend greatly on the priorities and constraints of the specific mission or scenario. Some possible constraints and tradeoffs would be range vs. power consumption, update rate vs. cost, target weight vs. maximum detectable range and accuracy desired, or size vs. power, heat dissipation, and capabilities. A decrease in the aperture size of the camera lens increases the depth of field of the camera and thus reduces the noise at longer ranges, but the optical power output must be increased for the target to be detectable at the same ranges.

The update rate could easily be increased because some of the video processing done is for the benefit of those observing the computer processed video. The rate could go to 3 Hz quite easily, and with the addition of a custom frame grabber, the expected update rate would be at least 5 Hz.

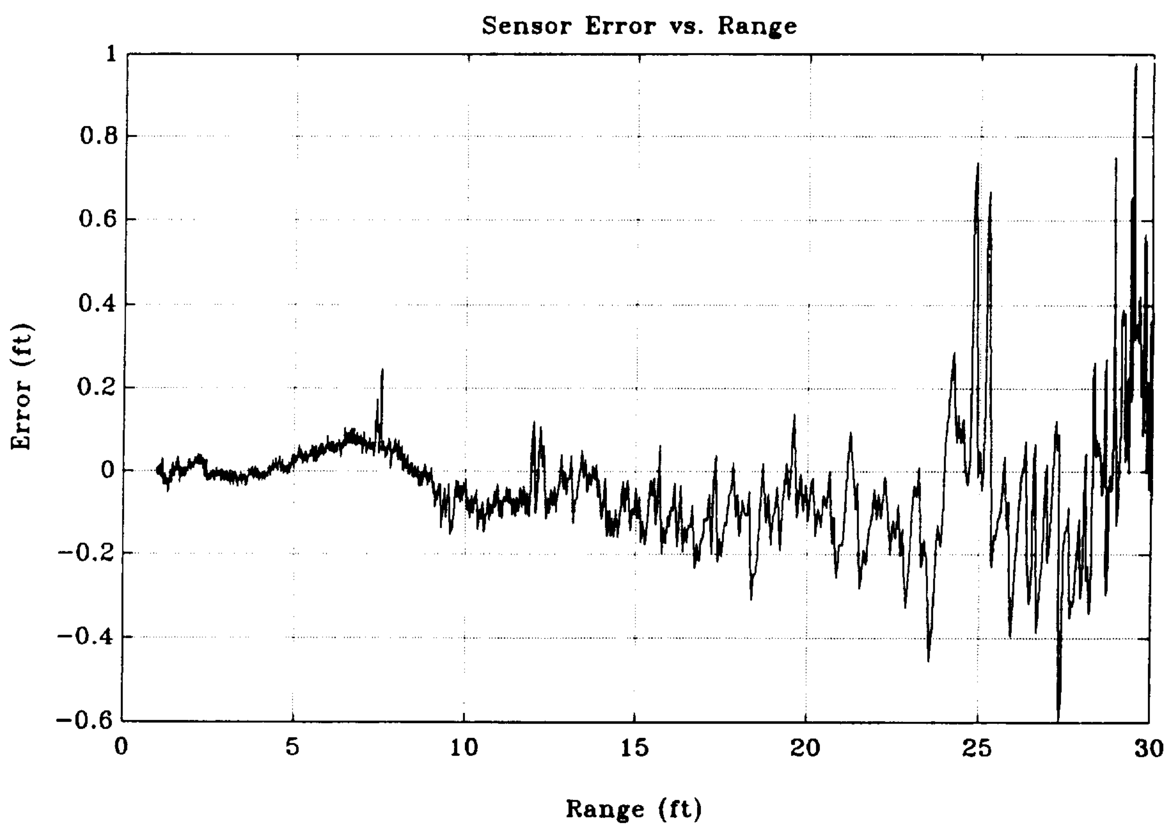
Several other possible improvements or tradeoffs are listed here with a brief description of the improvements and costs: a zoom lens would allow longer ranges, but would require more power to illuminate the target properly and would not be usable at short ranges; a variable focus lens would be more accurate at most ranges, but would require moving parts; focused laser diodes could be used to allow longer ranges, but more power would be require as would more laser diodes; narrower bandpass optical filters would mean that solar lighting would have a narrower range of interference, but the maximum pitch and yaw attitudes would be decreased.

VIDEO DOCKING SENSOR CHARACTERISTICS

Characteristic	Current Sensor Value	Future Sensor Value
Maximum Range	40 feet	150 feet
Solid Angle Area Covered	30 x 30 degrees	30 x 30 degrees
Data Update Rate	2 Hz	5 Hz or more
Attitude Limits (Pitch & Yaw)	+/- 40 degrees	+/- 40 degrees
Roll Limit	+/- 180 degrees	+/- 180 degrees
Attitude Rate	6 deg/sec	15 deg/sec
Bearing Angle Rate	1 deg/sec	2.5 deg/sec
Range Rate	5 ft/sec	12.5 ft/sec
Direct Sunlight	not within +/- 40 deg	not within +/- 10 deg
Physical Parameters		
Weight	N/A	8 lbs
Size	N/A	1/4 cubic ft
Power Consumption	30 Watts	10 Watts

Accuracies and Noise Levels

The accuracy of the sensor is a function of range, as are the noise levels. The longer the range, the more noisy and less accurate the data is. This stems from the fact that the lens is a fixed-focus lens that is focused at close ranges, so the long range picture is blurred, leading to variations in the target's reflections between frames and causing greater digitization inaccuracies. However, it was decided that the greater accuracy is required at close ranges rather than far ranges. A larger target that uses corner-cube retro-reflectors has a much steadier return at longer ranges, and it has a maximum range of 150 feet with the current sensor.


Sensor Error vs. Range
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
Error (ft)
0
5
10
15
20
25
30
Range (ft)

Planned and Potential Uses

Some of the planned and potential uses include the continued testing of autonomous docking algorithms in large-scale hardware in six degrees-of-freedom at up to the full length of the MSFC Flight Robotics Laboratory, soon to be 140 feet. Another possible use of this video-based sensor would be as a man-assisting berthing alignment sensor for the common module berthing during the Space Station Freedom assembly. Miniature versions of the sensor, employing only one or two illuminators due to the short ranges, could be used to allow automated alignment and positioning of robotic end effecters. In the future, any of several systems will require autonomous docking capabilities, and this sensor will be ready to meet the need.

PLANNED AND POTENTIAL APPLICATIONS FOR THE VIDEO BASED SENSOR

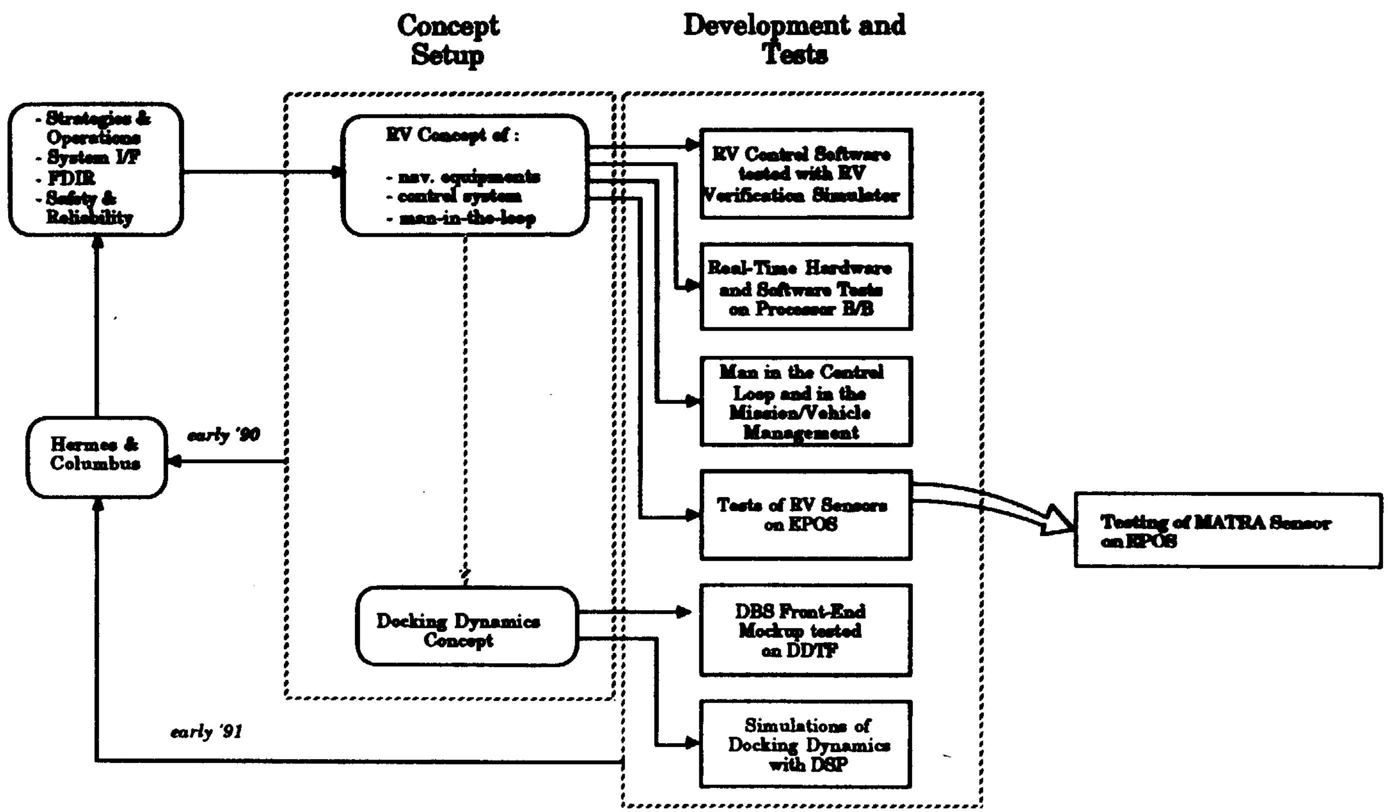
- TESTING OF AUTONOMOUS DOCKING ALGORITHMS IN A LARGE-SCALE SIX DEGREE-OF-FREEDOM ENVIRONMENT
- EMPLOYING IT AS AN ALIGNMENT SENSOR FOR COMMON MODULE BERTHING DURING SPACE STATION FREEDOM ASSEMBLY
- USING MINIATURE VERSIONS TO ALIGN OR GIVE SENSOR FEEDBACK TO AN OPERATOR PERFORMING ROBOTIC TELE-OPERATION
- SEVERAL PLANNED NASA SYSTEMS WILL REQUIRE AUTONOMOUS DOCKING

Description and Performances of the MATRA CCD Camera Sensor

C. M. Pauvert; T. Bomer
MATRA ESPACE
Toulouse
France

MATRA ESPACE

Utilization of MATRA CCD Camera Sensor within European RV System Pre-Development Programme



Specifications used for Sensor Design

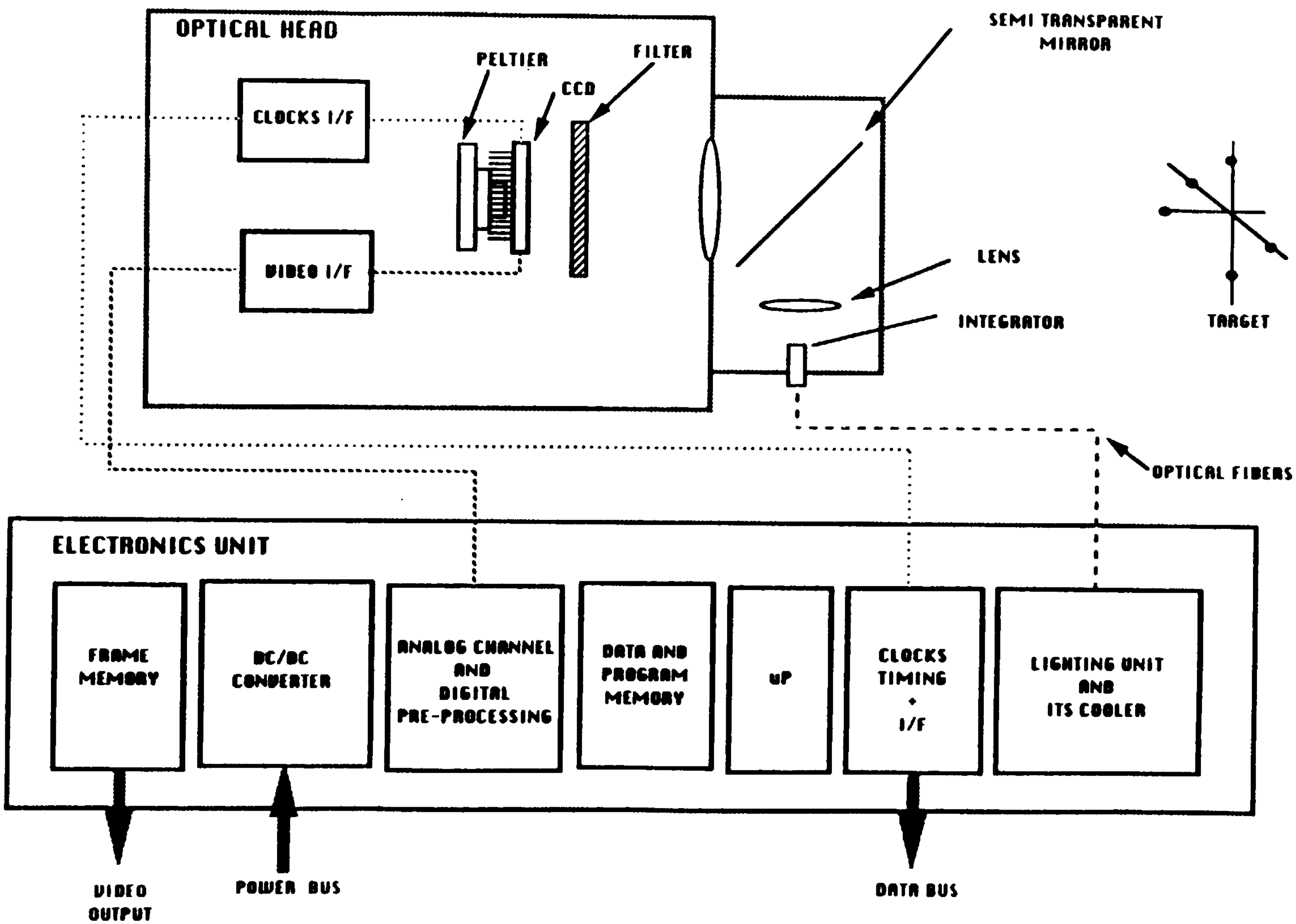
Parameters	Medium Range	Short Range	Proximity
Range	1 km - 250 m	250 m - 20 m	20 m - 0 m
Field of View	10° x 10°	10° x 10°	10° x 10°
Range Accuracy	4% - 2% (1km) - (250m)	2 %	2 %
LOS Accuracy	0.05 °	0.05 °	0.05 °
Relative Attitude Accuracy	—	—	0.5 °
Frequency	1 Hz	1 Hz	1 Hz
Optical Disturbances	Nominal Performances with sun in field of view or lighting by target		

Measurement Principles of the MATRA CCD Camera Sensor

- ➜ generation of a laser pulse during image acquisition
- ➜ no rotation/translation mechanism (better fiability)
- ➜ collection of light reflected on photo sensitive area
- ➜ detection performed by CCD array detector, synchronized with Flash During Transfer (FDT) mode (MATRA patent)
- ➜ FDT minimizes straylight influence $\Rightarrow$ excellent optical disturbances rejection
  $\Rightarrow$ allows use of sensor with sun in field of view

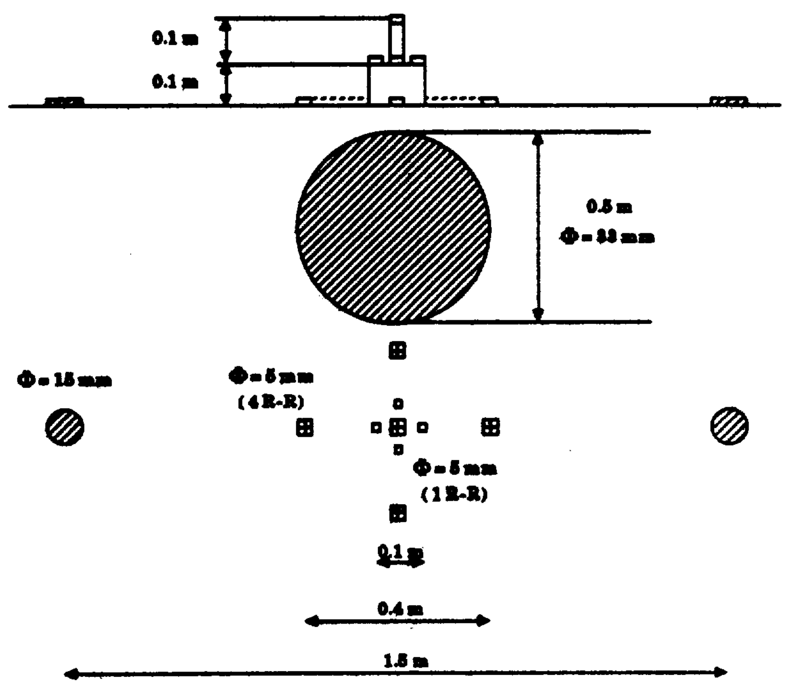
	Lidar Mode	Imager Mode
Operational Range	1 km $\Rightarrow$ 200 m	200 m $\Rightarrow$ 0.5 m
Operations	• acquisition of 2 images using FDT (2 different frequencies) • image processing and measurement of echoes positions • computation of time of flight and LOS	• acquisition of 1 image using FDT • image processing and measurement of echoes positions • provision of measurement information
Provided information	• Range • Line Of Sight (α, β)	• Range • Line Of Sight (α, β) • Relative Attitude (θ_x, θ_y, θ_z)

Functional Overview of the MATRA CCD Camera Sensor



Target Patterns

Range	1km/100m	200m/10 m	20m/2m	4m/0.5 m
sensor mode	Lidar	Imager	Imager	Imager
global diameter of each point	0.5 m	0.012 m	0.012 m	0.0006 m
distance between 2 farthest points	-	1.5 m	0.4 m	0.1 m
height of central point of pyramid	-	-	0.2 m	0.1 m
angle of incidence	± 20	± 20 °	± 20 °	± 20 °
number of R-R	180	70	4	1
diameter of each elementary R-R	33 mm	15 mm	5 mm	5 mm



Operating Modes of the MATRA CCD Camera Sensor

➜ Initialisation mode

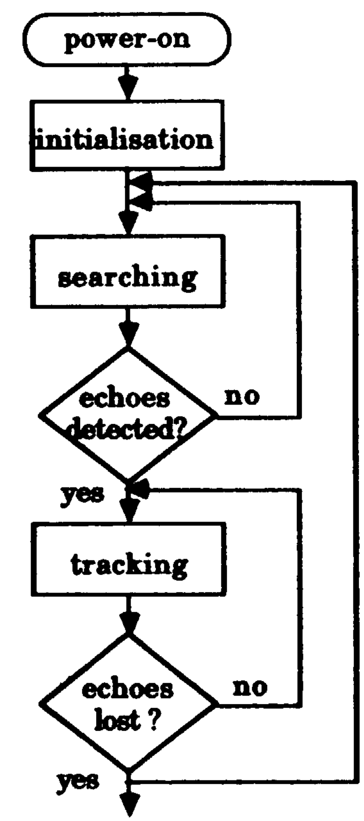
- hardware initialisation
- detector cooling
- nominal performances reached a few minutes after power-on

➜ Searching

- search of echoes in whole filed of view (threshold crossing)
- performs coarse measurement (±1 pixel)
- performs coherence test between location of echoes
- mode repeated until echoes are detected
- duration < 1 s if echoes in field of view

➜ Tracking

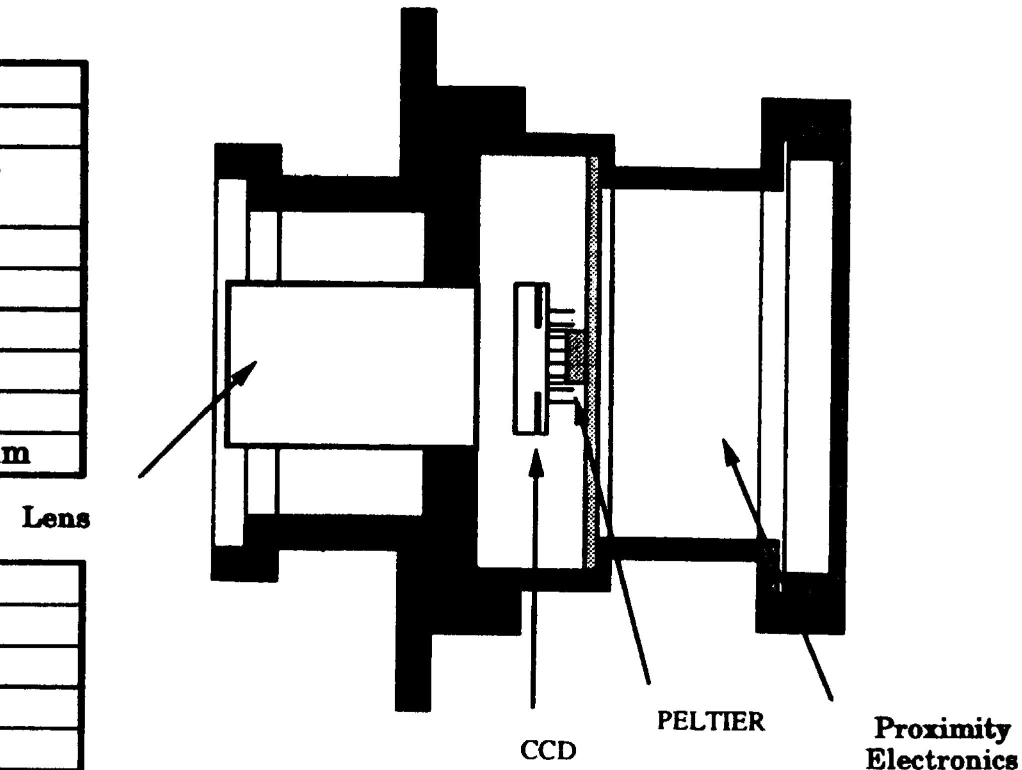
- fine measurement on echoes position
- compute state vector (R, LOS, $\underline{\theta_r}$)
- measurement rate > 1 Hz
- possible simultaneous tracking of 5 echoes



Characteristics of the MATRA CCD Camera Sensor

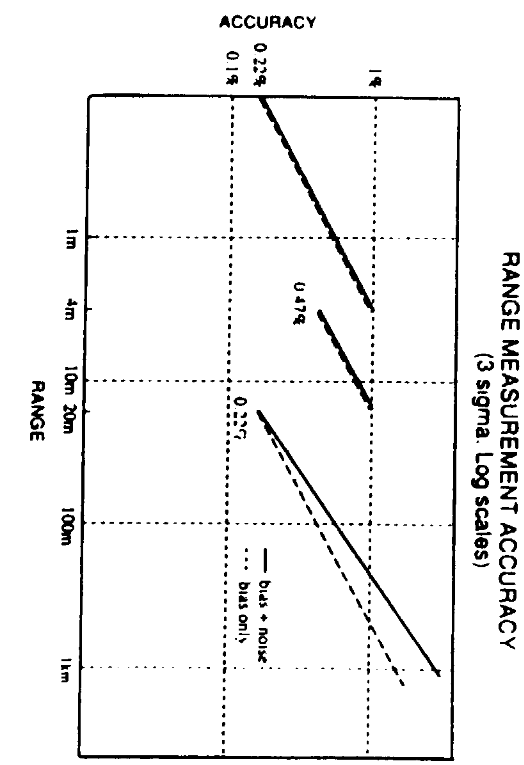
Optical Head	
Field of view	10° x 13°
Aperture	5 mm
Detector	Thomson TH 7863 (cooled 5°C)
Space distorsion	≤ 0.1 pixel
Image quality	0.5 pixel (1 km)
Time noise	± 15 ns
CCD noise	≤ 100 electrons
Transfer frequency	5 MHz
Size	110 mm x Φ108 mm

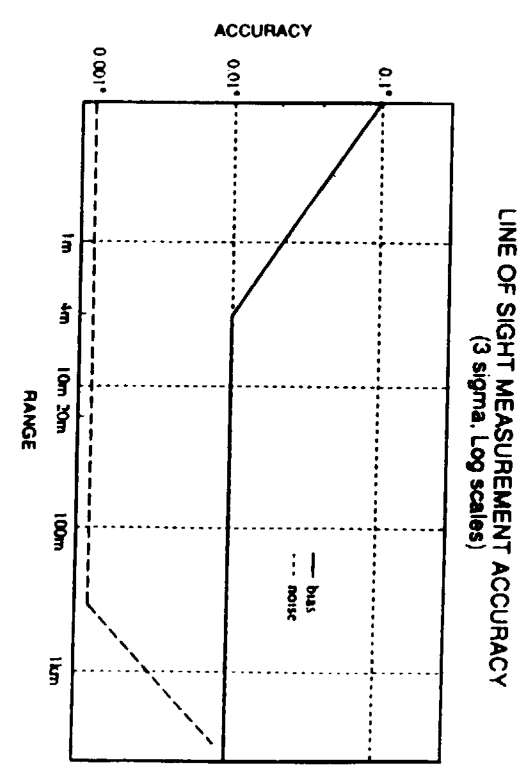
Lighting Unit	
Emitted energy	80 μ joules (1 km)
Pulse width	200 ns
Wavelenght	900 nm
Emission field of view	> 10° x 13°
Consumption	≤ 2W (mean)
Mass	< 1 kg

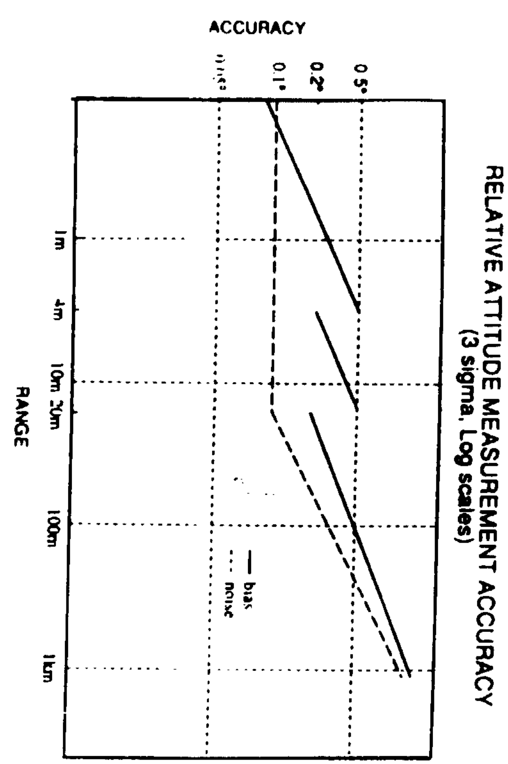


Performances of the MATRA CCD Camera Sensor

- ➔ LOS accuracy 0.05° (R > 0.5 m)
- ➔ range accuracy 1 % (R < 200m)
- ➔ relative attitude accuracy ≤ 0.5°







Performances of Sensor in Closed-Loop

- closing velocity = 5 mm/s
- docking of Hermes with earth-pointing CFF
- switch-off of target AOCS for port-to-port distance = 1.00 m

	Navigation performance at chaser AOCS switch-off (0.10 m)
θ_x (roll)	0.2 °
θ_y (pitch)	0.2 °
θ_z (yaw)	0.2 °
Ω_x	1.2 10^{-3} °/s
Ω_y	2.0 10^{-3} °/s
Ω_z	2.0 10^{-3} °/s
X (along docking axis)	20 mm
Y (out-of-plane)	4.5 mm
Z (to earth)	1.5 mm
$\dot{X}$	0.30 mm/s
$\dot{Y}$	0.35 mm/s
$\dot{Z}$	0.20 mm/s

- increase of approach velocity (e.g. 20 mm/s) does not significantly affect overall performance
- other missions (HMS/CFF sun-pointing, HMS/SSF) do not change overall performance

Performances of Sensor in Closed-Loop

→ contribution of the various error sources to performances at chaser AOCS switch-off

	relative attitude	relative att. rate	lateral position	lateral velocity	axial velocity
range bias	-	-	-	-	-
range noise	-	-	-	-	65 %
LOS bias	-	-	20 %	-	-
LOS noise	-	-	-	ε	-
rel. att. bias	85 %	-	70 %	-	-
rel.att.noise	10 %	95 %	10 %	95 %	15 %
external perturb.(*)	5 %	5 %	ε	5 %	20 %

perfos	0.2 °	$\leq 2.0\ 10^{-3}$ °/s	≤ 5 mm	≤0.35 mm/s	≤ 0.30 mm/s

(*) differential air drag & plume impingement (20 N cold gas thrusters)

Testing of MATRA Sensor on Docking Dynamics Test Facility

➔ test performed in closed-loop on DDTF (CNES/MATRA Test Bed [Ref. 1])

➔ chaser (Hermes) :
- breadboard of CCD Camera Sensor
- simulated gyros
- simulated thrusters

target (CFF) :
- simulated gyros
- simulated thrusters

➔ Chaser ⇒ liquid sloshing

Target ⇒ liquid sloshing + structural flexibility

➔ Chaser : Prediction of $\underline{X}_r$ and $\underline{\theta}_r$ (based on gyros)

Position and attitude state update with RV sensor measurements (R, LOS, $\underline{\theta}$)

➔ Target : Limit cycle on attitude (1°, bandwidth 0.016 rad/s, damping ratio 0.7)

➔ Dynamic tests for ranges from 6 m ⇒ nearly contact (measured range ≥ 0.5 m)
Misalignments on angular attitude (roll/pitch/yaw) and on lateral position

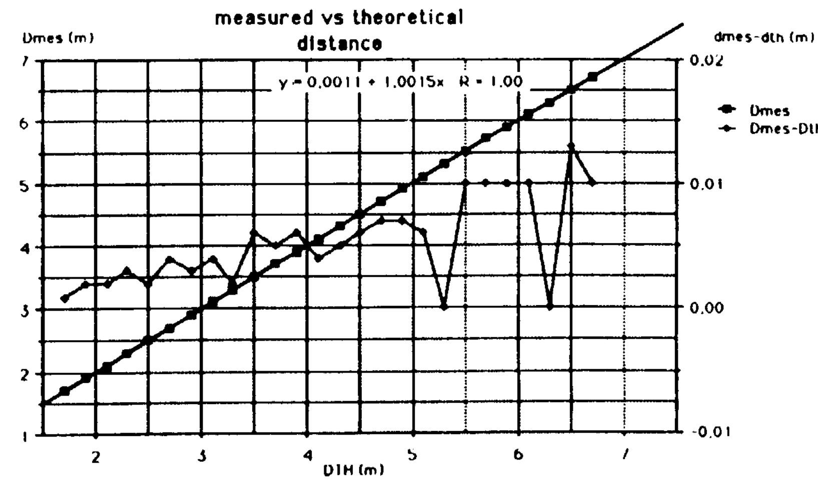
Testing of MATRA Sensor on Docking Dynamics Test Facility (cont'd)

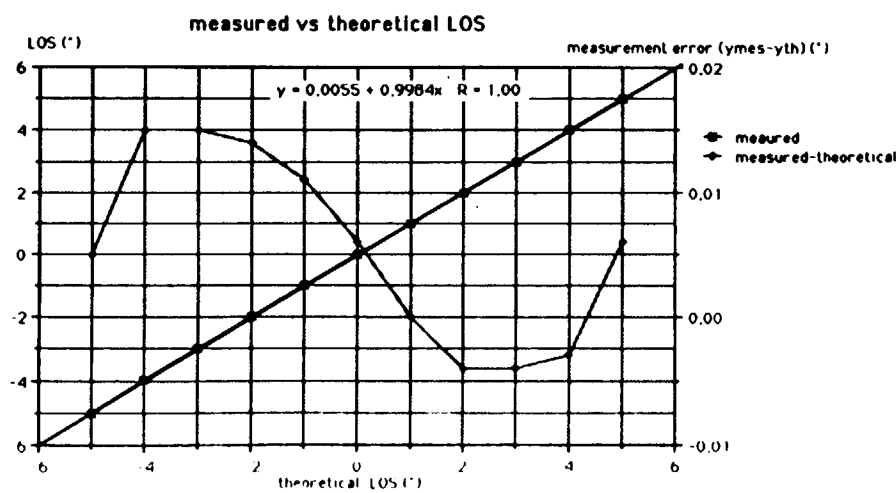
➜ Measurement rate = 8Hz

➜ Simplified relative position dynamics (Clohessy-Wiltshire) including differential drag and plume impingement

➜ Test results confirm in closed-loop the performances assessed in open loop

ΔR	< 1 % of R
Δ LOS	< 0.01 °
$\Delta\theta$	< 0.5 ° on all axes ↘ when R ↘

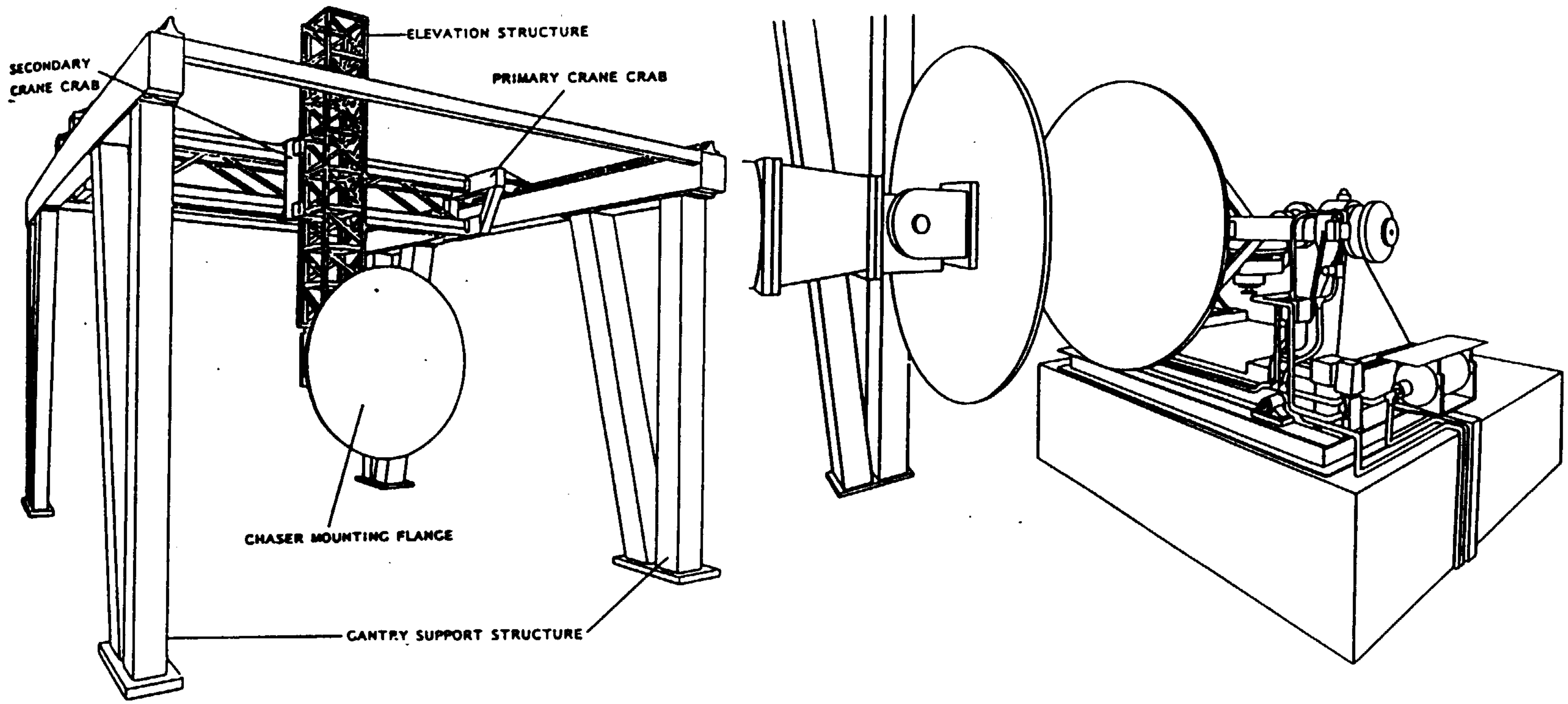




Testing of MATRA Sensor on European Proximity Operations Simulator

- ➜ tests of optical sensors performed in the frame of the European Proof-Of-Concept programme
- ➜ tests performed on the European Proximity Operations Simulator (EPOS)
- ➜ dynamics relative linear/angular motion of 2 spacecraft (6 DOF's)
- ➜ illumination of sensor performed by dedicated sun simulation subsystem (2 DOF's)
- ➜ test of sensor tracking capability
- ➜ test range : 10 m $\Rightarrow$ 0.5 m typically
  misalignments and angular (3 axes) and linear lateral position
- ➜ test of sensor performances wrt a reference sensor system
- ➜ testing of different optical sensors breadboards manufactured in Europe
- ➜ test campaign from November '90 to April '91

Testing of MATRA Sensor on European Proximity Operations Simulator

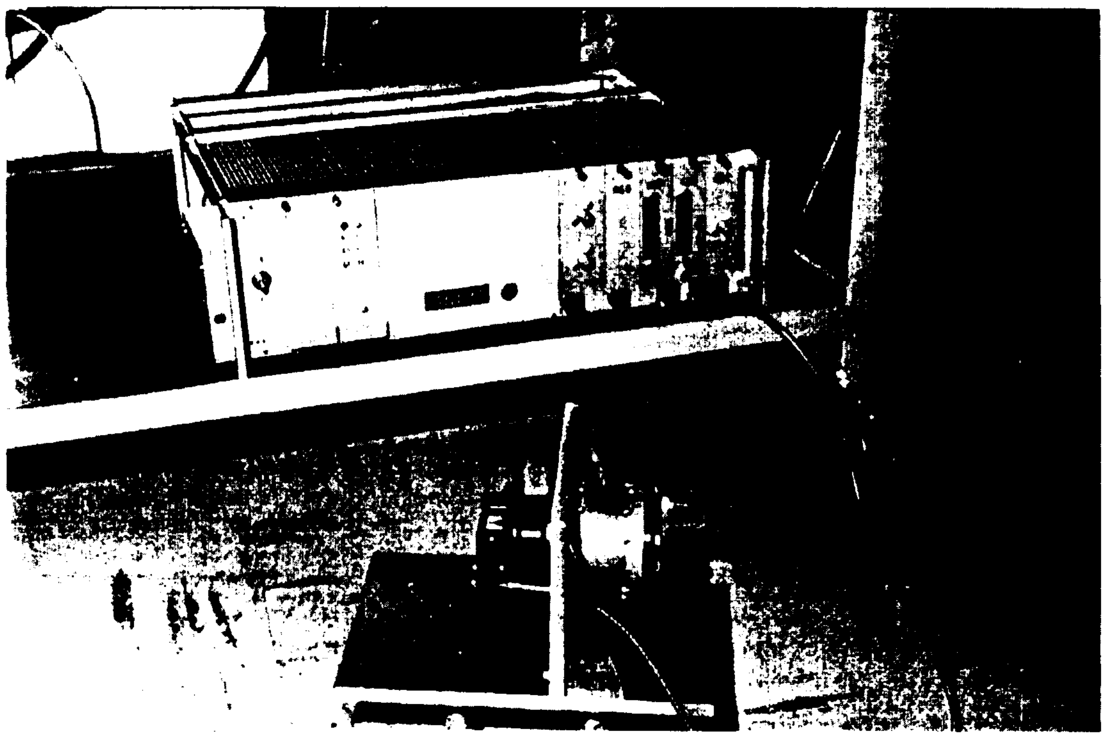


Description and Performances of the MATRA CCD Camera Sensor

CONCLUSIONS

- ➔ MATRA CCD Camera Sensor meets requirements for docking mission of Hermes with CFF
- ➔ MATRA CCD Camera Sensor meets requirements for berthing of CFF with SSF [ref 2]
- ➔ MATRA CCD Camera sensor may operate in any lighting conditions (FDT mode)
- ➔ one single target pattern may be used for final translation 20 meters → contact
- ➔ target pattern for medium range (2 retro-reflectors / 1.5 m) → no requirement on background lighting
- ➔ breadboard has been developed and tested on dynamics test bed without special care on calibration/supply aspects ("on-the-shelf" procurement)
- ➔ possible field of application in space robotics (contacts with Fairchild, ORU's manipulation on SSF)

RENDEZ-VOUS SENSOR BREADBOARD (PICTURE)



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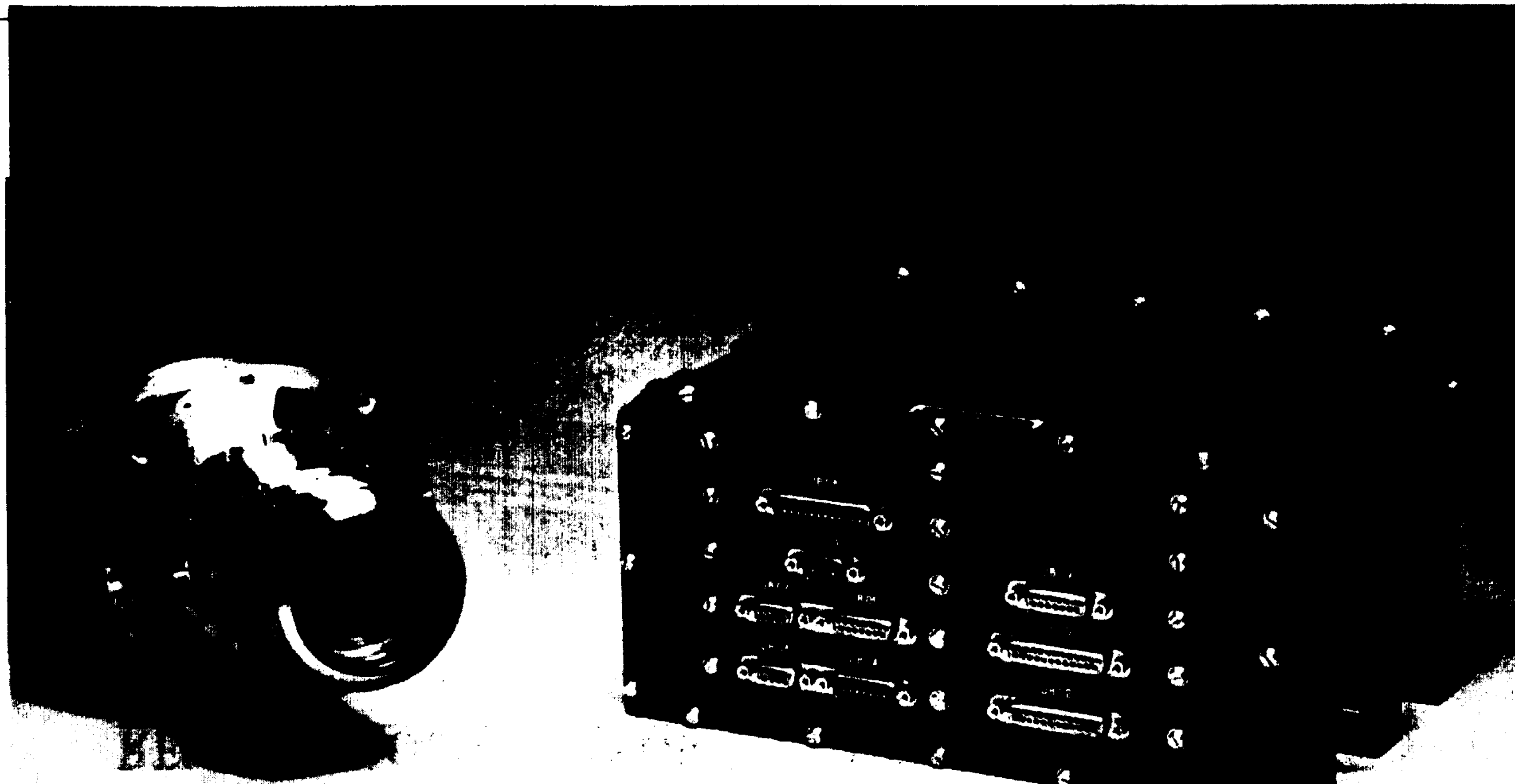

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Description and Performances of the MATRA CCD Camera Sensor

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Activities reported in this presentation have been performed in the frame of the Technology Programme of the French Space Agency (CNES) for the sensor design and development, and the closed-loop testing on DDTF, and of the Technology Programme of the European Space Agency (ESA) for the sensor performance assessment and the verification on EPOS

LASER DOCKING SENSOR

PRESENTED TO
AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

JOHNSON SPACE FLIGHT CNETER
AUGUST 15-16, 1990

PREPARED BY
Joseph L. Prather
NASA-JSC

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

LASER DOCKING SENSOR PROGRAM OVERVIEW

Joseph L. Prather NASA Johnson Space Center August 15, 1990

- ★ Development funded by Office of Space Flight, Advanced Systems Branch
- ★ Tentatively planned to support 1996 flight demonstration of the Satellite Servicer System
- ★ McDonnell Douglas Space Systems Company is the prime contractor
- ★ Presently performing a systems trade study to determine the most appropriate method for implementing the performance requirements using optical techniques

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

LASER DOCKING SENSOR PROGRAM OVERVIEW

Joseph L. Prather — NASA Johnson Space Center — August 15, 1990

SCHEDULE

★ Trade Study Complete	- November 1990
★ PDR	- September 1991
★ CDR	- June 1993
★ Engineering Model Delivery	- December 1993
★ Qualification Testing	- June 1994 to February 1995
★ Flight Hardware Delivery	- August 1995
★ Flight Demonstration	- August 1996

SCHEDULE DRIVEN BY FUNDING PHASING

LASER DOCKING SENSOR PROGRAM OVERVIEW

Joseph L. Prather NASA Johnson Space Center August 15, 1990

POTENTIAL APPLICATIONS

- ★ Satellite Servicer System
- ★ Lunar/Mars Missions
- ★ Orbiter Rendezvous Missions
- ★ Space Station

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

LASER DOCKING SENSOR PROGRAM OVERVIEW

Joseph L. Prather NASA Johnson Space Center August 15, 1990

Tentative Laser Rendezvous and Docking Sensor Performance Requirements

PARAMETER	LIMIT	ACCURACY (u + 3s)
RANGE (R):	0.5 m -185 Km	±0.03R meters
MAX RANGE RATE::	± 100 m/sec (function of range)	±0.04R^1/3 m/sec
BEARING ANGLE (AZ and EL):	± 10 Deg	± 1/R^1/3 Deg for R < 300 meters ± 0.15 Deg for R > 300 meters
BEARING ANGLE RATE:	± 1 Deg/sec	± 0.06/R^1/3 Deg/sec for R < 300 meters ± 0.009 Deg/sec for R > 300 meters

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

LASER DOCKING SENSOR PROGRAM OVERVIEW

Joseph L. Prather NASA Johnson Space Center August 15, 1990

Tentative Laser Rendezvous and Docking Sensor Performance Requirements (Cont.)

PARAMETER	LIMIT	ACCURACY (u + 3s)
ATTITUDE (fine): (Pitch and Yaw)	$\pm$ 10 Deg	0.9 Deg
Pitch and yaw (course):	4pi Steradian	TBD Deg
ATTITUDE (Roll) (fine):	$\pm$ 180 Deg	0.9 Deg
MAX ATTITUDE RATE (fine):	$\pm$ 6 Deg/sec	0.03 Deg/sec
MAX ATTITUDE RATE (course):	TBD Deg/sec	TBD Deg/sec

Maximum attitude range is 100 meters

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

LASER DOCKING SENSOR PROGRAM OVERVIEW

Joseph L. Prather NASA Johnson Space Center August 15, 1990

Tentative Laser Rendezvous and Docking Sensor Performance Requirements (Cont.)

★ Size:	0.06 cubic meters maximum
★ Weight:	30 Kg maximum
★ Power:	175 watts maximum

Tentative Laser Rendezvous and Docking Sensor Performance Requirements (Cont.)

Probability of Acquisition 99.9%

Probability of False Alarm 1 per 10^6 pulses

Acquisition Time

Initial Acquisition:	5 min @ 185 Km
	3 min @ 92.5 Km
	1 min $\leq$ 10 nmi
Planned Acquisition:	30 sec
Tracking Loss Acquisition:	30 sec
Deploy Acquisition:	30 sec

Carrier vehicle provides nominal target range and bearing to LDS

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

LASER DOCKING SENSOR PROGRAM OVERVIEW

Joseph L. Prather — NASA Johnson Space Center — August 15, 1990

CANDIDATE TECHNIQUES

RANGE:

Pulse Ranging for Long Range

Tone Ranging for Close-in

Holometrix, Inc. is developing a high speed counting circuitry to determine range using time-of-flight technology over short ranges (< 1Km) (NASA JSC funded Phase I SBIR)

Autonomous Technology Corporation is developing a CO_2 scanning LADAR which can also provide bearing and attitude measurements (NASA JSC funded Phase II SBIR)

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

LASER DOCKING SENSOR PROGRAM OVERVIEW

Joseph L. Prather   NASA Johnson Space Center   August 15, 1990

CANDIDATE TECHNIQUES (cont.)

BEARING:

Angular resolver sensors on scanning mirrors

Pixel location on CID/CCD cameras

ATTITUDE:

Imaging Approaches

- Scanning Laser Rangefinder
- Passive Imaging: Video or IR Cameras

CANDIDATE TECHNIQUES (cont.)

ATTITUDE MEASUREMENTS (cont.)

Non-imaging Approaches:

McDonnell Douglas is developing the following approaches:

- Interference Filter Array
- Prism Array
- Digital Imaging Radiometry
- Retroreflector Array

Applied Research Incorporated is developing a technique to derive attitude measurements using a single retroreflector (NASA JSC funded Phase II SBIR)

Hybrid (Optical and Digital) Image Processing for Vision-Based Control

PRESENTED TO

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

JOHNSON SPACE FLIGHT CENTER

AUGUST 15-16, 1990

PREPARED BY

Richard D. Juday

Tracking and Communications Division

NASA Johnson Space Center

Hybrid (Optical and Digital) Image
Processing Vision-Based Control

Richard D. Juday
Tracking and Communications Division
NASA Johnson Space Center

ABSTRACT

Hybrid vision is the result of image processing that is partly digital, partly optical. The Johnson Space Center program is discussed. Its main elements are spatial light modulators, video rate image coordinate transformations, Fourier optics filter optimization for signal-to-noise ratio, and synthetic estimation filters. A bibliography is given.

I. Introduction

Hybrid vision is the result of image processing that is partly digital, partly optical. Pattern recognition by digital image processing is a well enough known discipline, but in this context we use digital processing more for control interaction with a vision system than for pattern recognition. The pattern recognition is done by Fourier optics, with the heavy duty aspects being done using off-line calculations. The advantages devolving from the Fourier optics aspects are its speed and a possibly reduced amount of sensitivity to obstruction, deep shadow from solar illumination, etc. The Tracking and Communications Division has been working on hybrid vision for several years[1-36]. The elements are control system applications of correlators[1-13], spatial light modulators[14], methods of optimizing filters that are expressed under the constraints of real spatial light modulators[15-22], video rate image warping for machine vision applications[23-28] and human low vision[29-31], and some techniques[34-36] that were developed under funding from the Mars lander project. JSC has a memorandum of understanding with the U. S. Army Missile Command (MICOM) which is contributed to by the technology that is being developed. MICOM's interest is in developing missiles sufficiently smart enough and with good enough vision to do an autonomous "docking" of a missile with a tank. The analogy with spacecraft docking is immediately obvious. NASA wishes to reuse the system and hopes for a lower closing speed.

II. Correlation as a measurement tool

In hybrid vision, the information extraction is performed by optical correlation. An image is encoded by an input spatial light modulator operating on coherent light. Most of our work uses VanderLugt type correlation[1-6,8,10-12,15-22] and some[7,9,34-36] uses the joint transform. For autonomous rendezvous and docking applications there are two major technical elements, the "backscratching" algorithm[10] and the synthetic estimation filter[2,3,5,8-11,13]. Correlation, whether done optically or digitally, measures the degree of resemblance between the viewed object and the reference object. Optical correlation is notably susceptible to changes of appearance of the viewed object that one would ordinarily not wish to degrade the measurement. Scale and rotation sensitivity are the prime examples. We developed the backscratching algorithm to compensate. Measurements alternate being made in the ordinary Cartesian geometric representation of the object--which allows centration of the object--and in the log-polar representation, which allows imaging optics to correct the rotation and magnification of the image.

III. Pose estimation by SEF

Two bodies are spatially related by only six degrees of freedom. For AR&D purposes we separate them as follows. First and second are the latitude and longitude of the viewed object in the "sky" of the other. Third and fourth are the latitude and longitude of the viewpoint in the sky of the viewed object (this corresponds to out-of-plane motion of the viewed object). Fifth is the distance between viewer and object (roughly equivalent to in-plane scale). Sixth is the relative rotation of the pair about the line of sight (exactly equivalent to in-plane rotation in the imager plane of the viewing system). As mentioned in Section II we can use correlation under Cartesian and log-polar representation to make direct measurement of items 1, 2, 5, and 6 of this list. To handle items 3 and 4, traditionally the more difficult parameters to estimate, we have developed the synthetic estimation filter (SEF)[2,3,5,8,9,11,13] that works as follows. Synthetic (i.e. composited) views of the object are created exactly so that correlation strength, plotted against pose, has affine variation. With the tailored variation, simple computations yield robust estimates of the pose from a very few correlation measurements. We have recently[11] extended the concept to multiple dimensions of pose. Compared to an exhaustive search of filters, each sharply responding to one pose of the object, a reduction of the number of filters to be searched seems likely to be on the order of a factor of eight.

IV. Video rate image transforms

A unique technical element at the Johnson Space Center is the Programmable Remapper[23]. It will do a highly arbitrary geometric transform of a Cartesian image fed to it at video rate. It fits into the hybrid vision scheme in that optical flow can often be transformed into a pure translation. The classic example is that the log polar transformation produces a shift-invariant image flow as a Cartesian sensor is approaching normally to a plane. Optical correlation is by nature a shift-invariant operation, and so to modify a video image to produce pure translation conforms it for input to a pattern-recognizing optical correlator. Because almost any geometric transformation of a 2-D image can be done at video rates, we have been investigating[29-31] the application of the technology to human low vision. The idea is to warp the version of the world presented to the low vision patient so as to make best use of the remaining viable retina. An analogy is that the image warping as possible with the Remapper could create a better "impedance match" between the low vision eye and the world.

V. SLM's and SNR Optimization

We have worked toward the creation of filters that take into account the nature of the spatial light modulators on which they are expressed. In one sequence of papers[15-17,21] we take into account the coupling between phase and amplitude. In others[12,16] we adapt to behavior of the SLM that is unknown in detail. Elsewhere[18] we adapt to phase filtering with a modulator that is of quite limited range; we routinely achieve solidly detectable correlations with a phase modulator that is limited to about one radian (cf. 2π for full ability). We initially[17,21] maximized only the central correlation value, but more recently[22] have begun a move into filters that optimize signal-to-noise ratio (SNR) for additive random noise of known power spectrum in the transform plane and also filters that optimize SNR when detector noise is included.

VI. Summary

The Johnson Space Center is actively working on several technological areas that are applicable to autonomous rendezvous and docking.

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AUTONOMOUS TECHNOLOGIES CORPORATION

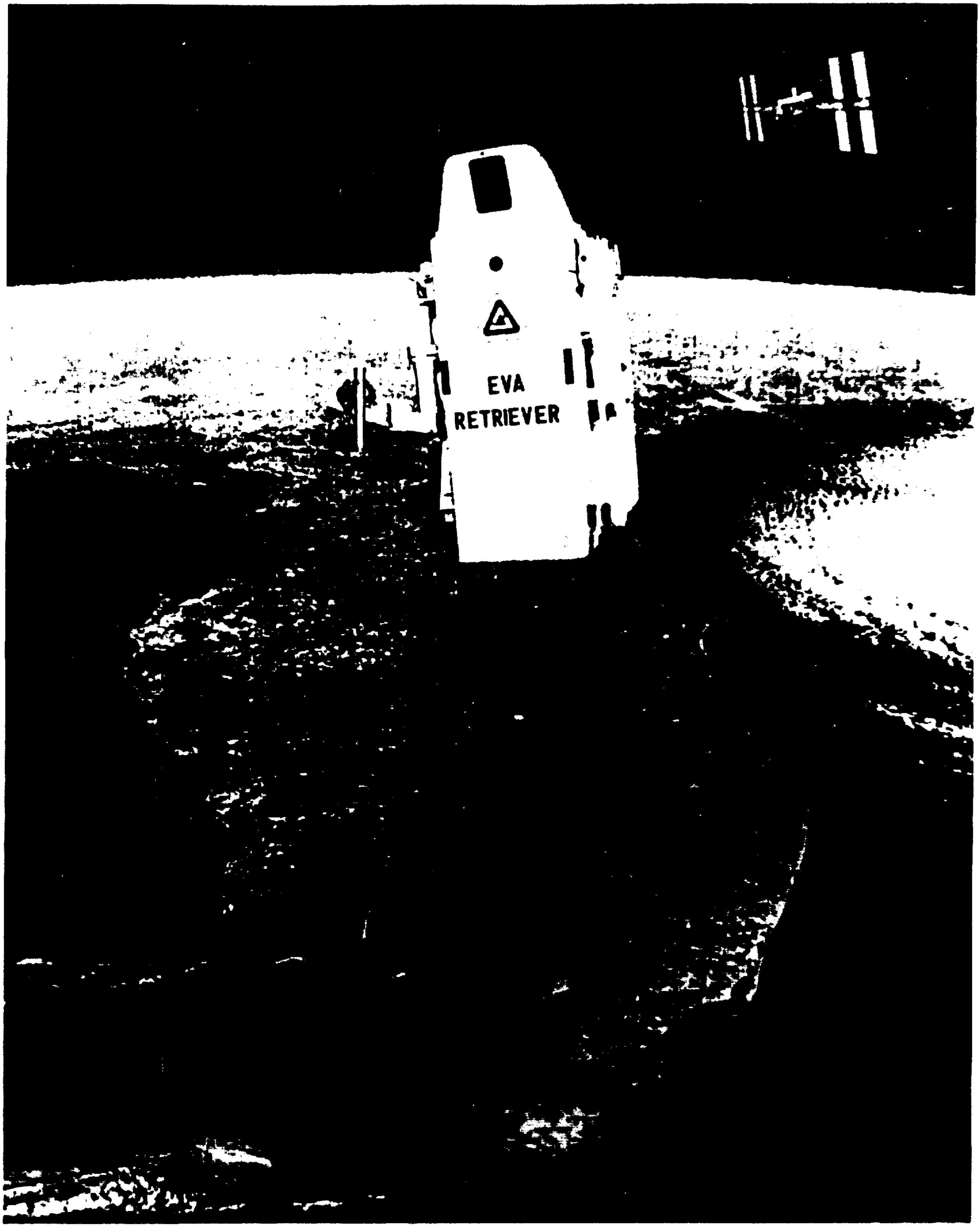
LADAR VISION TECHNOLOGY

FOR

RENDEZVOUS AND DOCKING

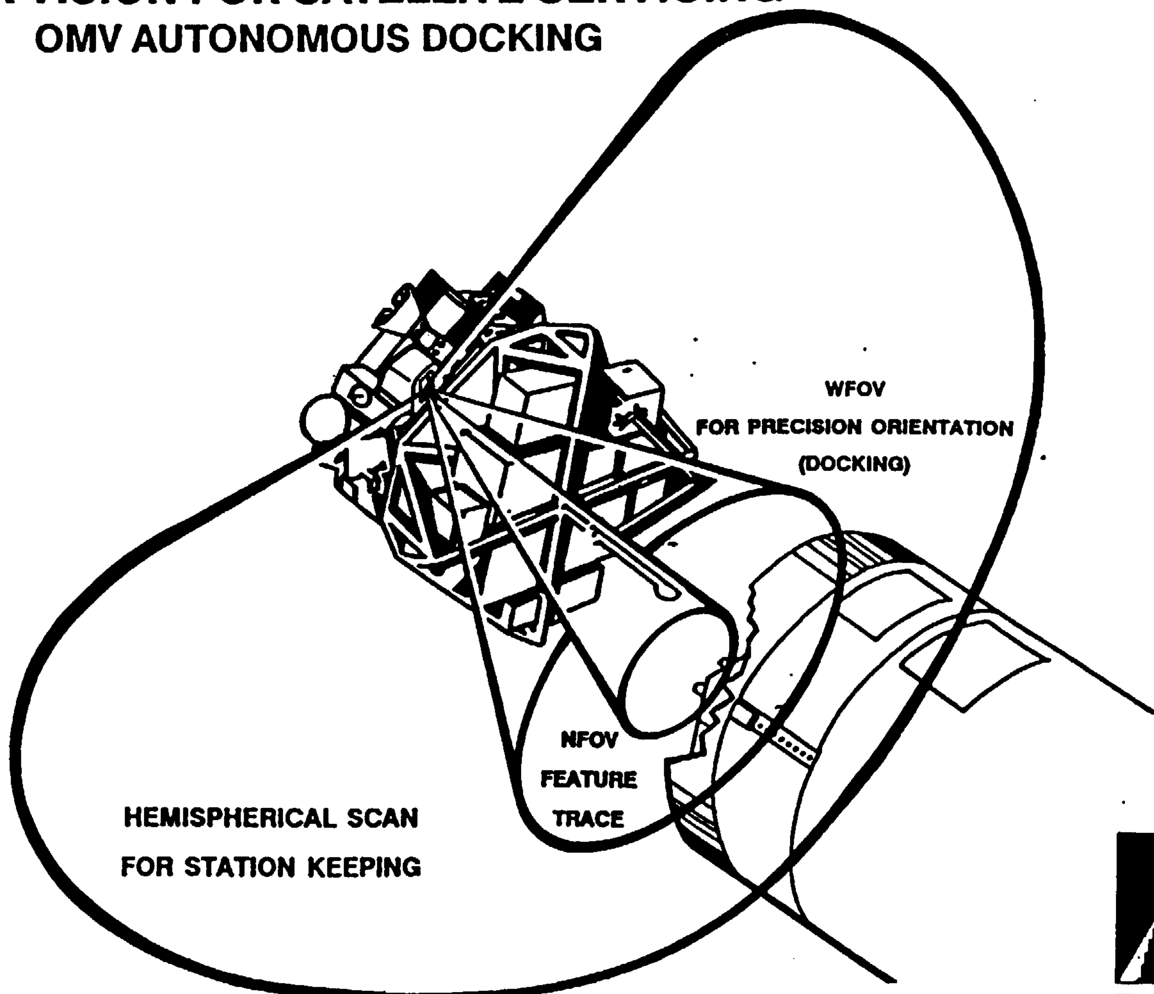
RANDY W. FREY

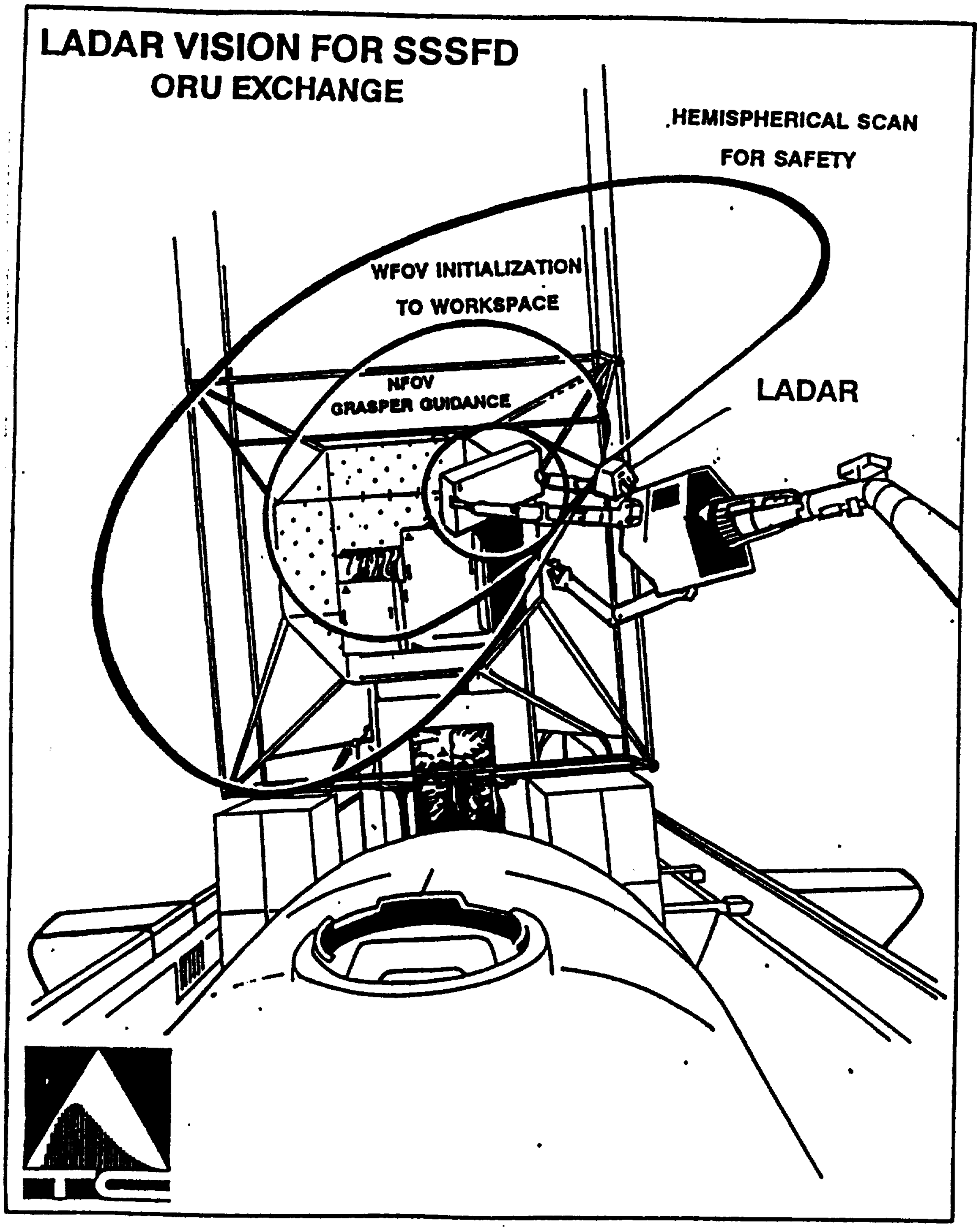
PREPARED FOR
THE AUTONOMOUS RENDEZVOUS AND
DOCKING CONFERENCE
AUGUST 15-16, 1990
NASA LYNDON B. JOHNSON SPACE CENTER



I-174

LADAR VISION FOR SATELLITE SERVICING
OMV AUTONOMOUS DOCKING




LADAR VISION FOR SSSFD
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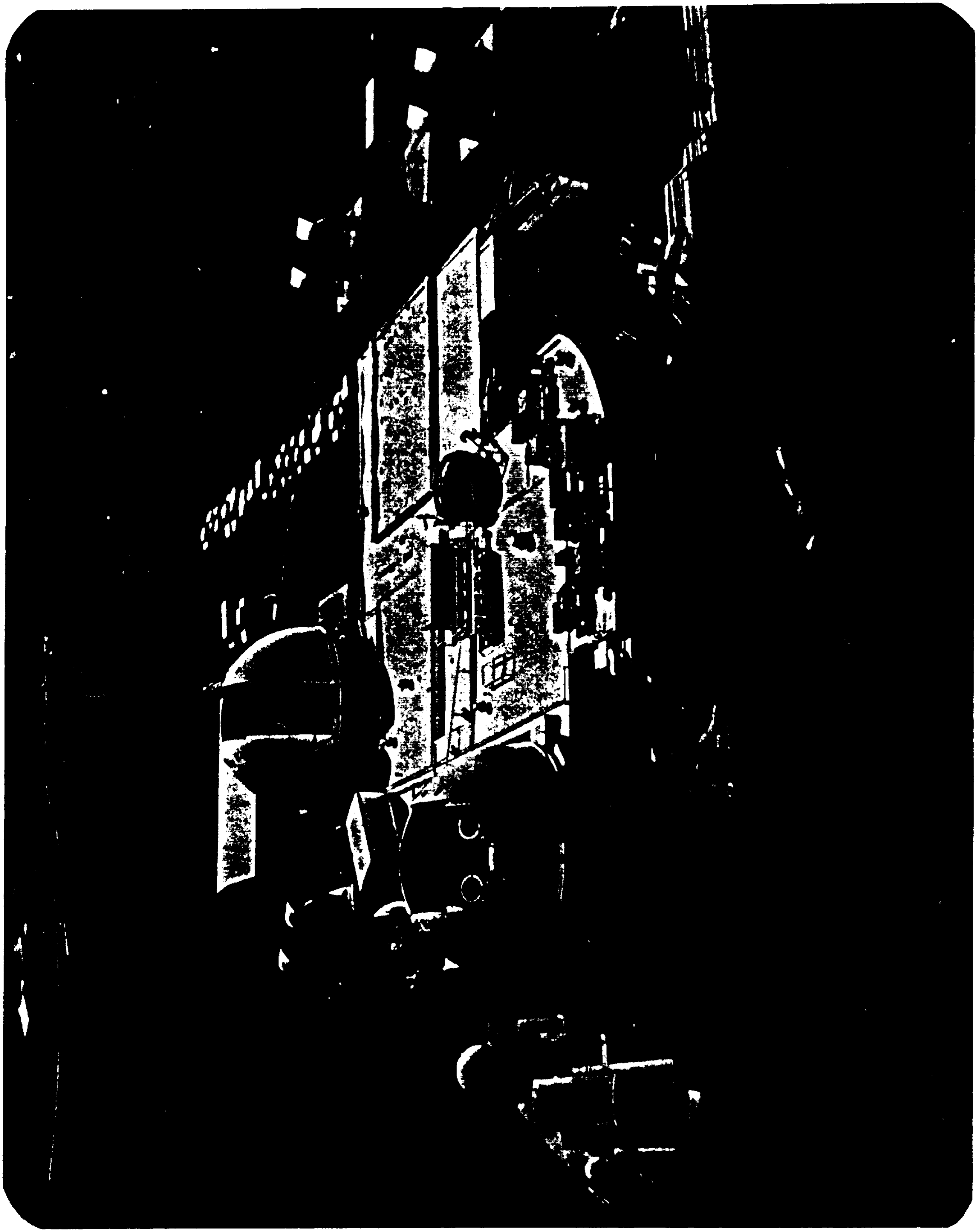
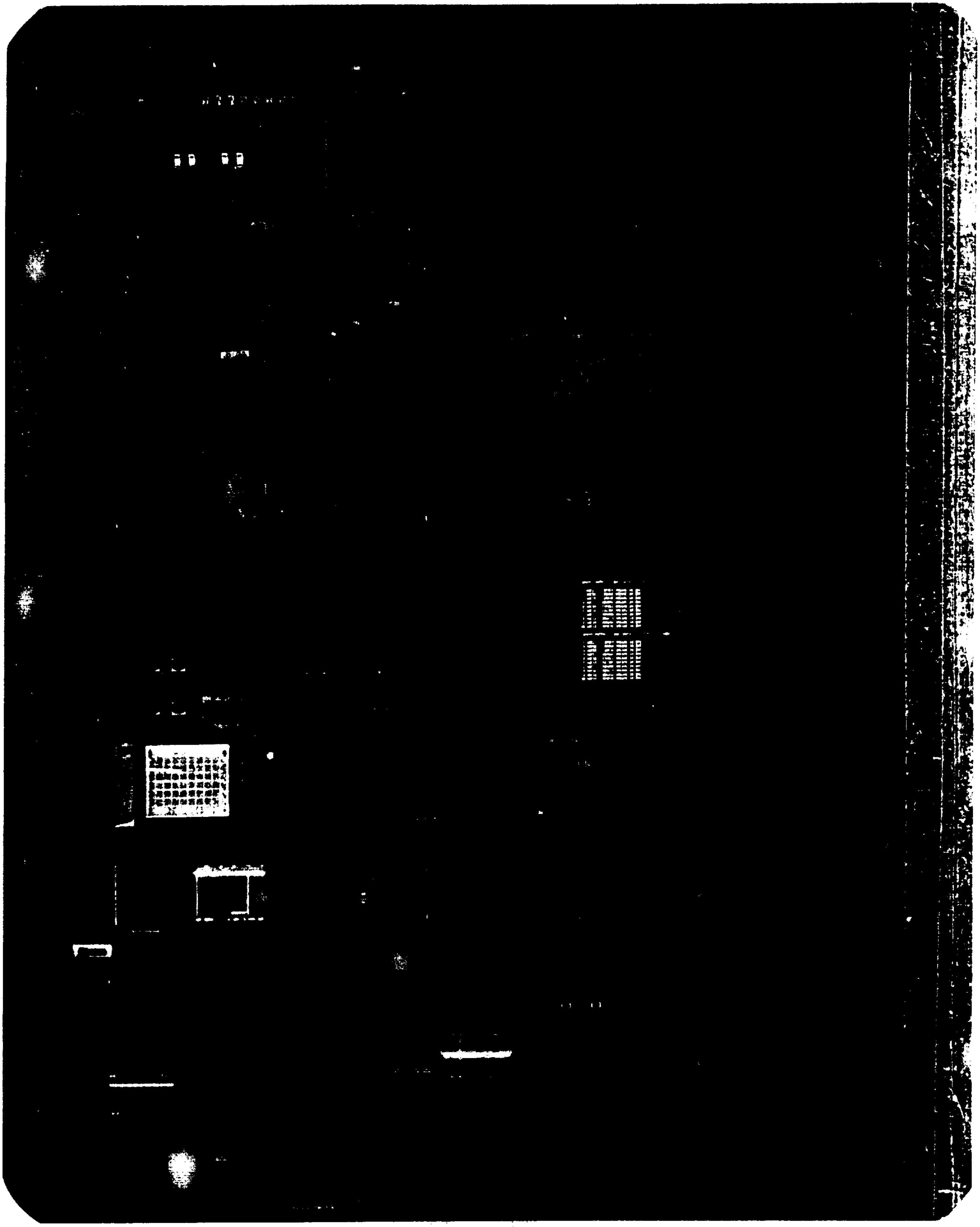
.HEMISPHERICAL SCAN
FOR SAFETY
WFOV INITIALIZATION
TO WORKSPACE
NFOV
GRASPER GUIDANCE
LADAR





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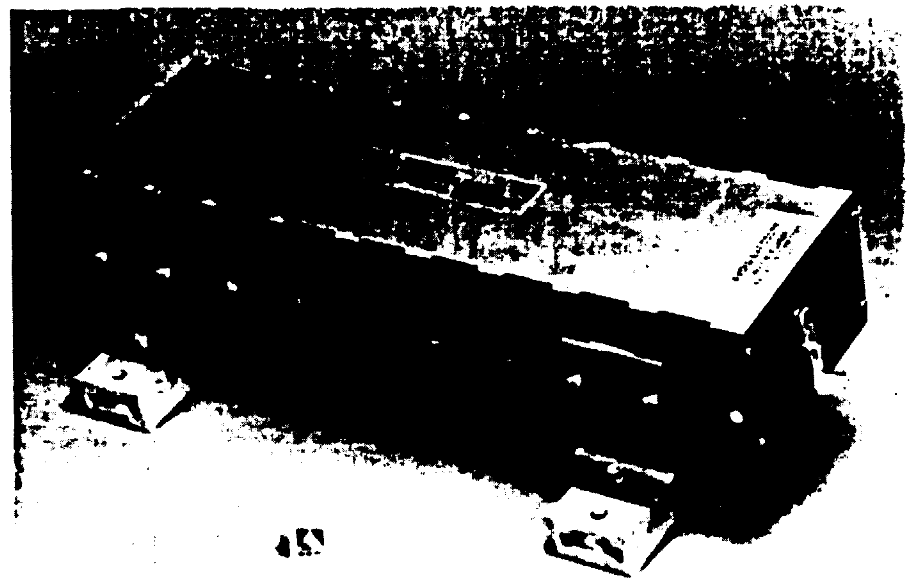
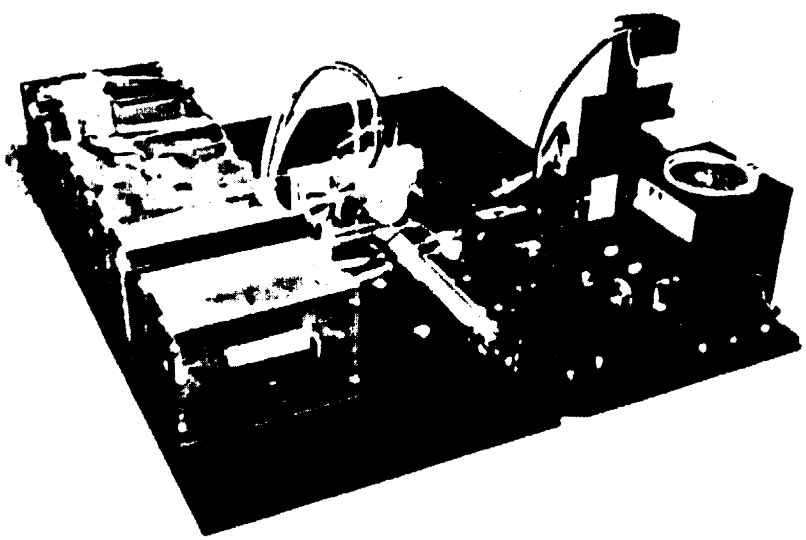
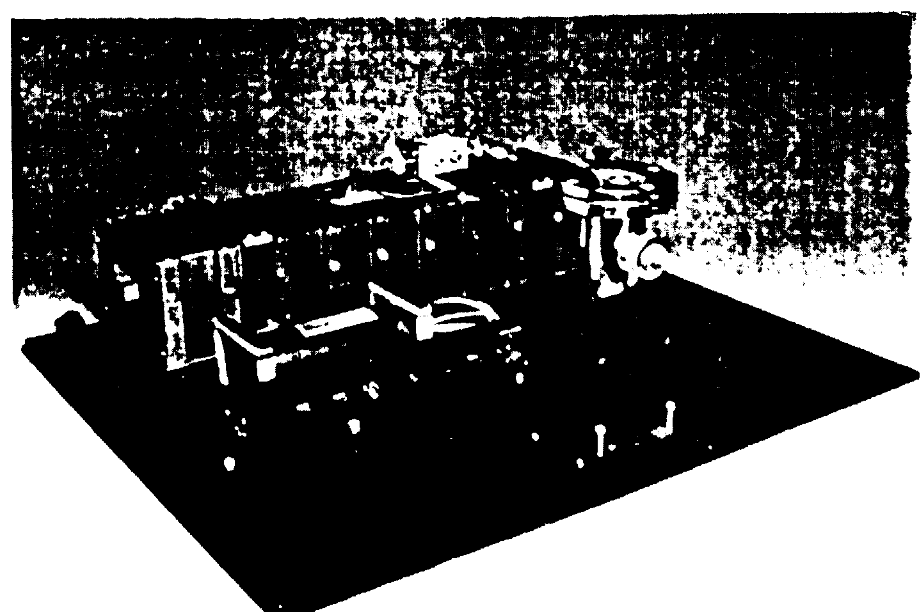


A. UTRC 50W COHERENT TRANSMITTER

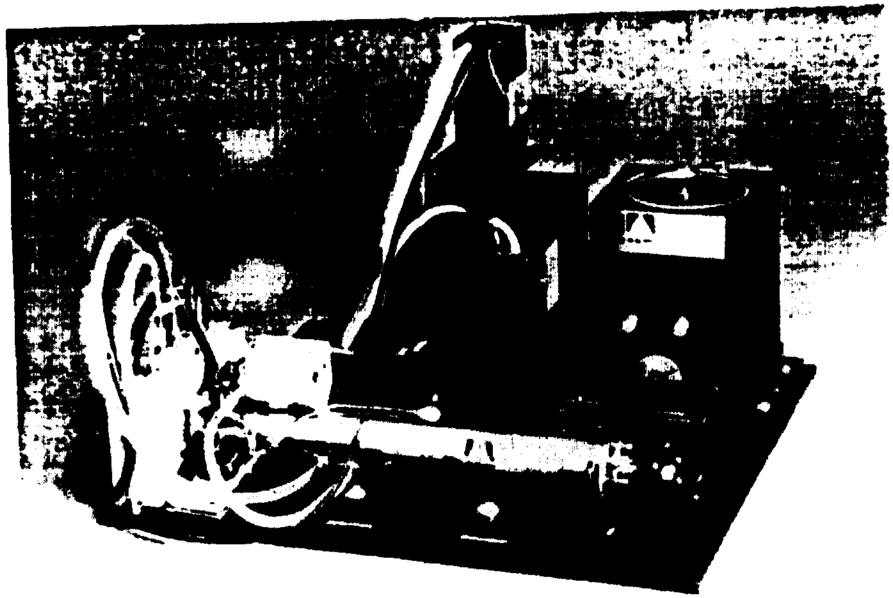


B. HOMODYNE EXPERIMENT WITH ATC IMAGING LADAR

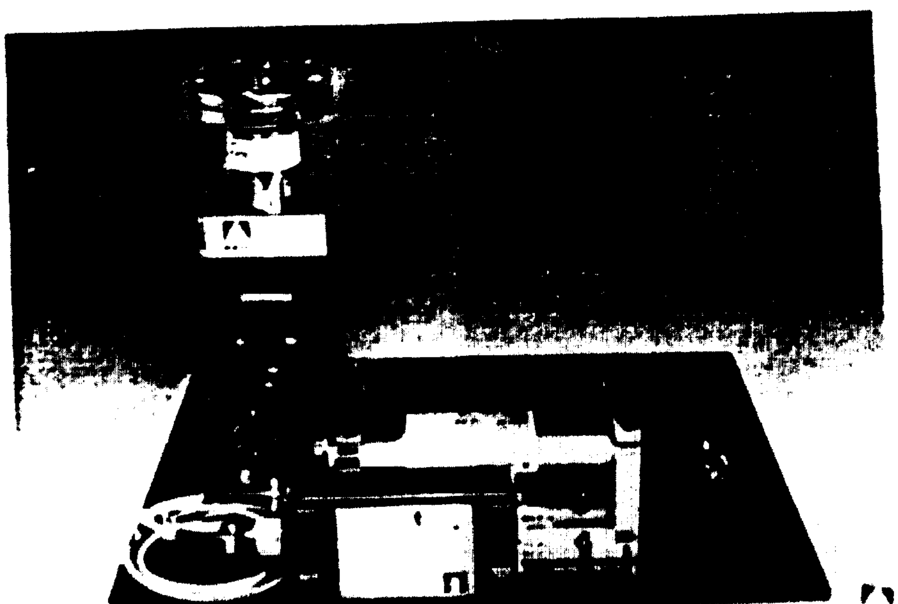


C. LASE 1.6M TRANSCEIVER MOCK-UP

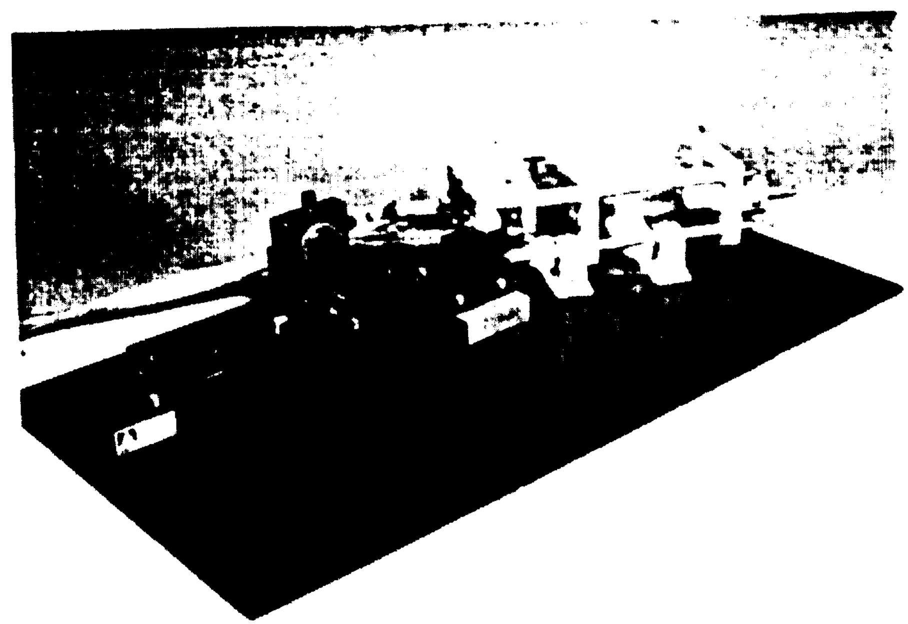
ATC LADAR OPTICAL PRODUCTS



A. ATC IMAGING LADAR



B. LASE FREQUENCY STABILIZATION SENSOR UNIT



ATC ONE MICRON LADAR, SEO LASER

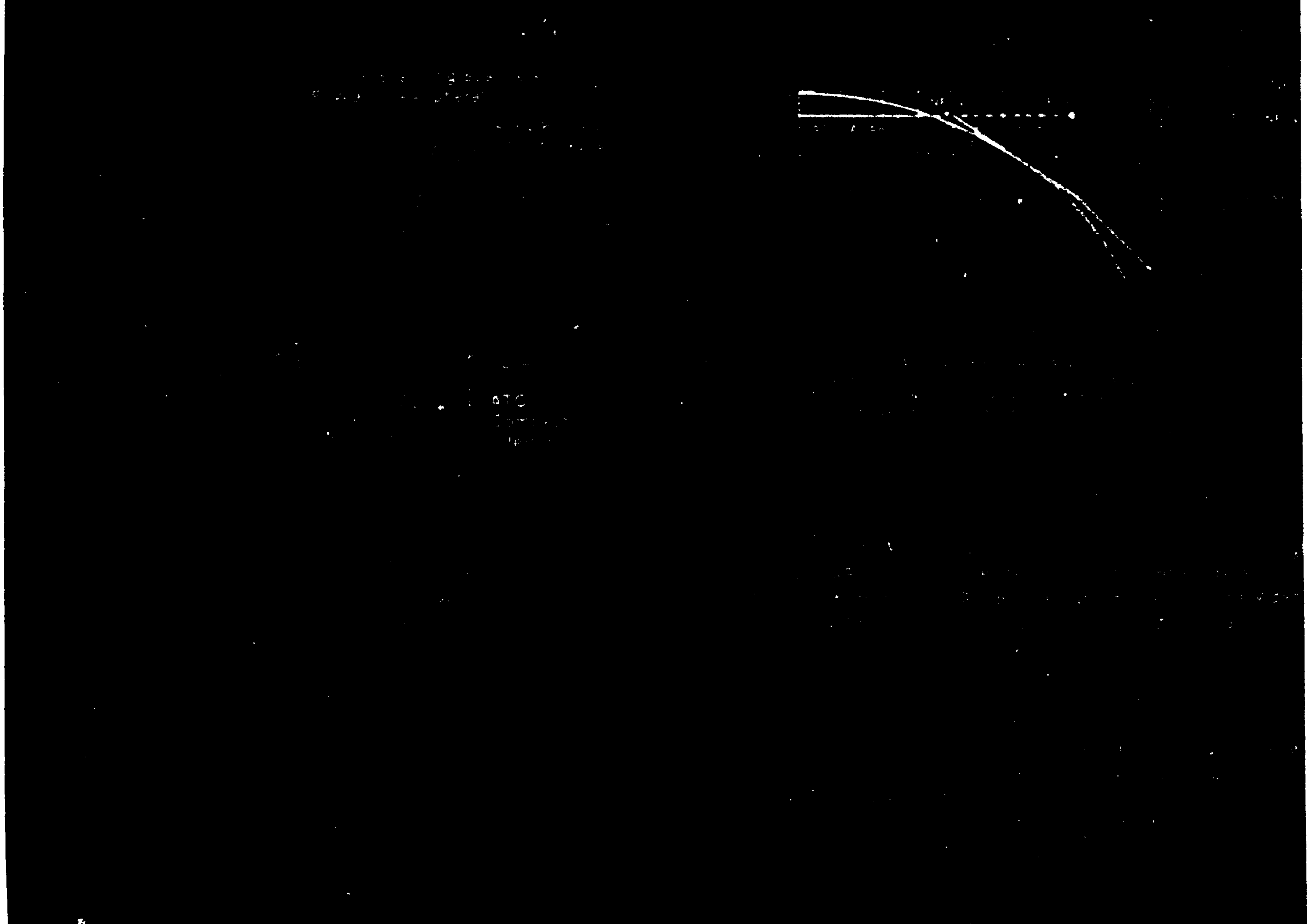
Why CO2 Laser Radar for LDS

- Eye Safe
- Long Range Capability
- Precise Range, Range Rate and Angle Tracking
- Highly Precise Short Range Differential Range, Range Rate and Angle Track
- Maturing State of Art
- Potential For 6DOF Track or Skin Track Targets (SDI SBIR Program)

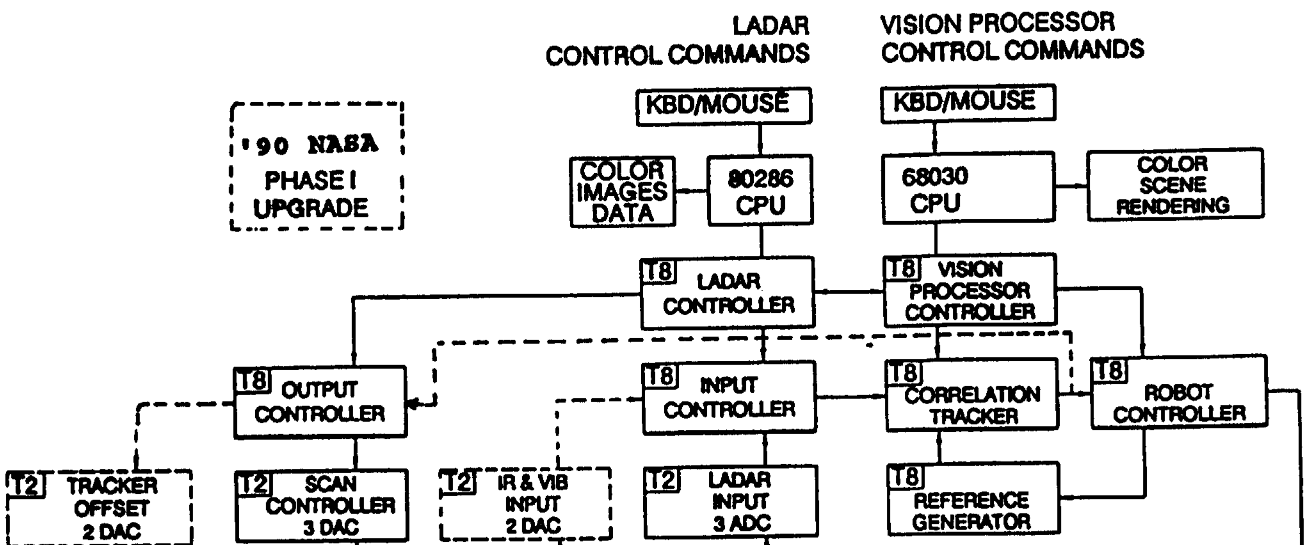
HUMAN EYE/BRAIN SEGMENTATION

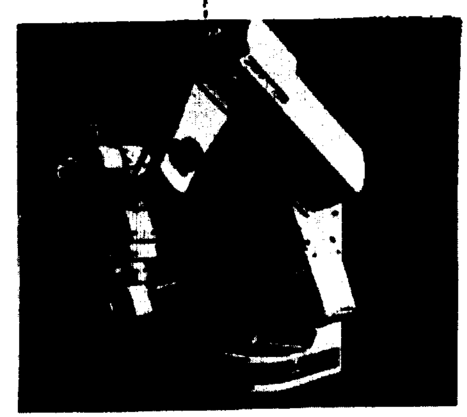
EYE	LADAR
COLOR	INTENSITY
SHAPE/CONTOUR	3D RANGE
MOTION DETECTION	VELOCITY

ATC IMAGE LADAR



PHASE I A. CONFIGURATION (SUMMER '89) FOR SDI SBIR "ADAPTIVE GRASPING"

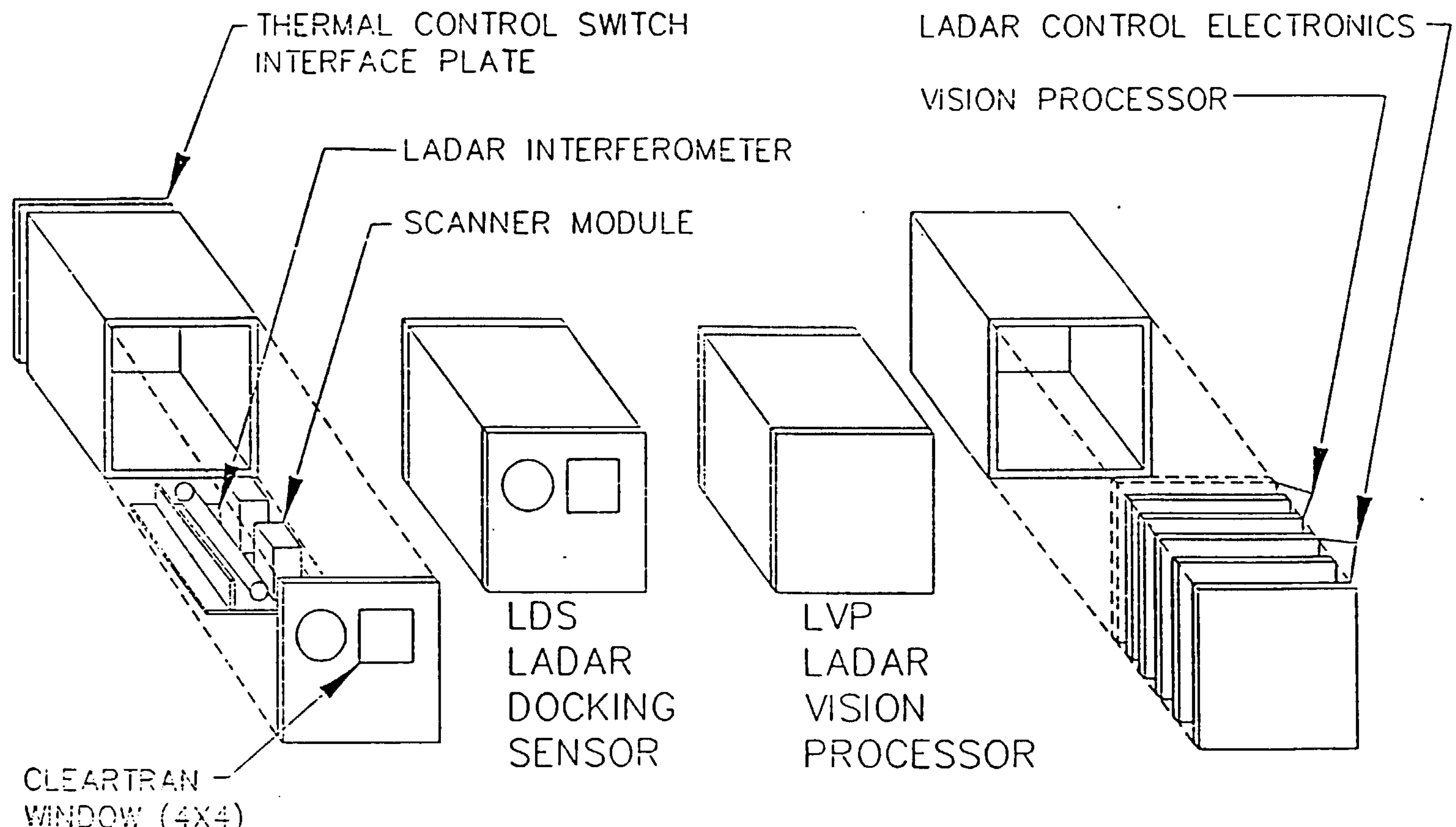




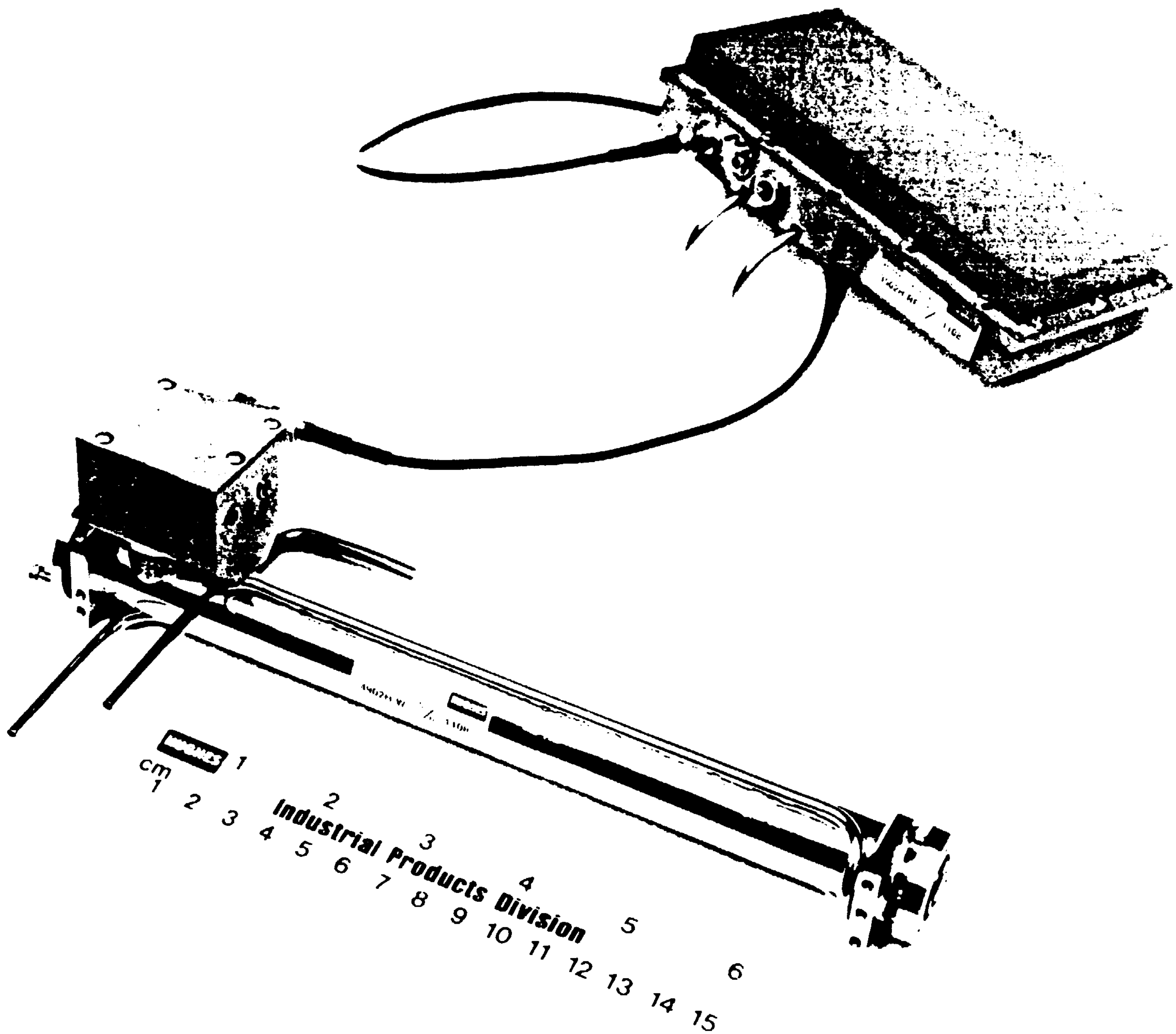
(Loan from Honeybee Robotics, NYC)

ATC LADAR VISION ROBOTIC CONTROLER TESTBED

Research is Sponsored by: SDIO/IST
and Managed by: U.S. Army SDC-Huntsville, AL.



LVS = LADAR VISION SYSTEM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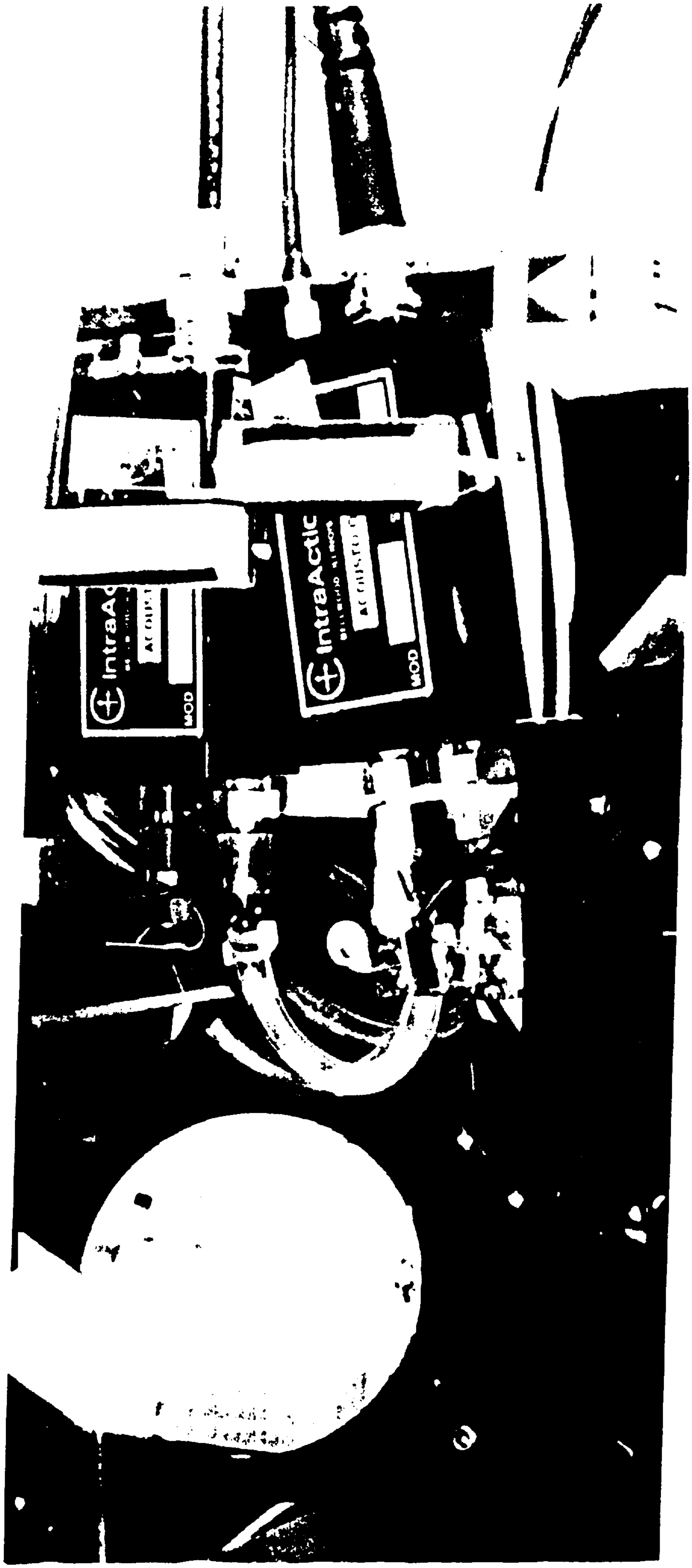
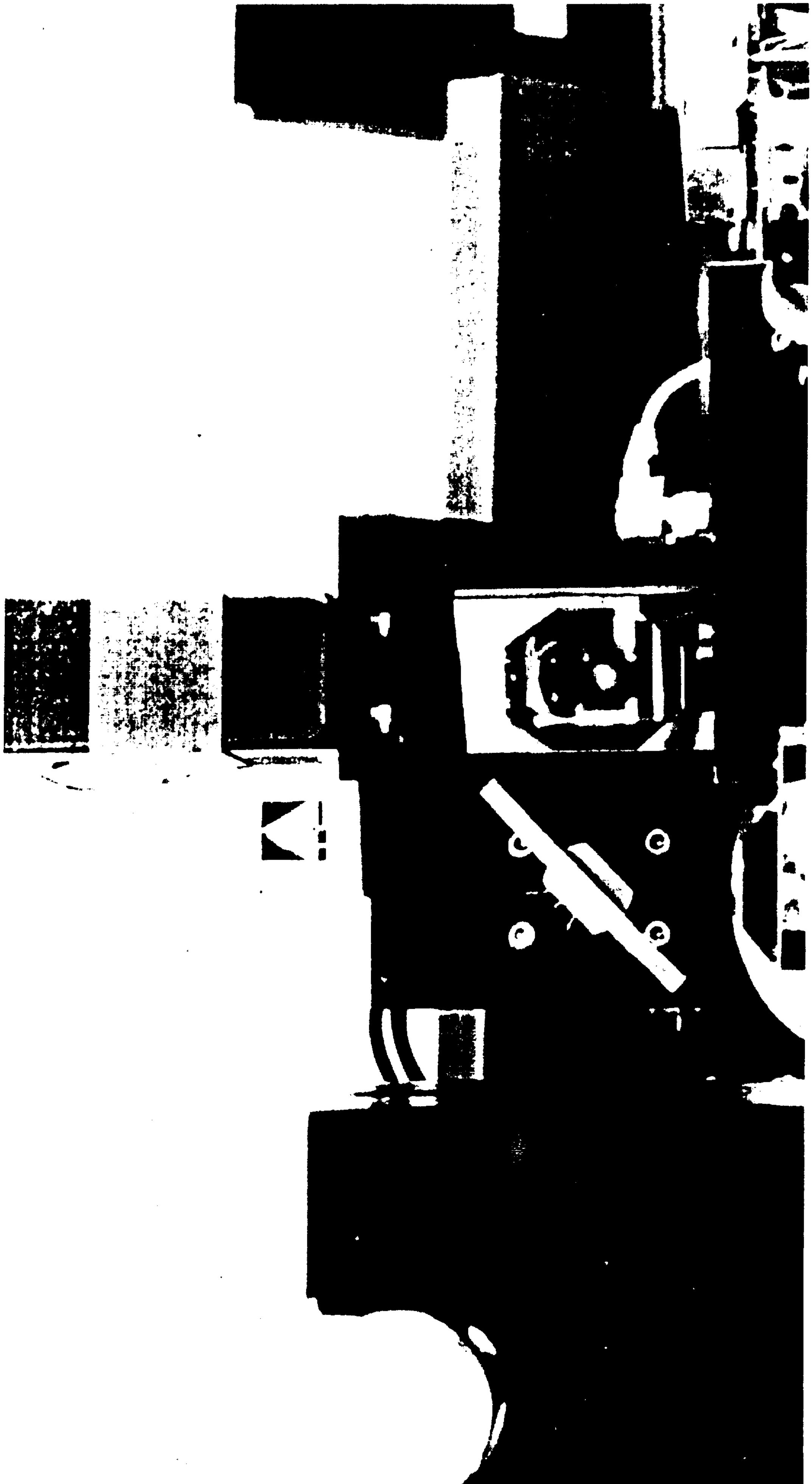
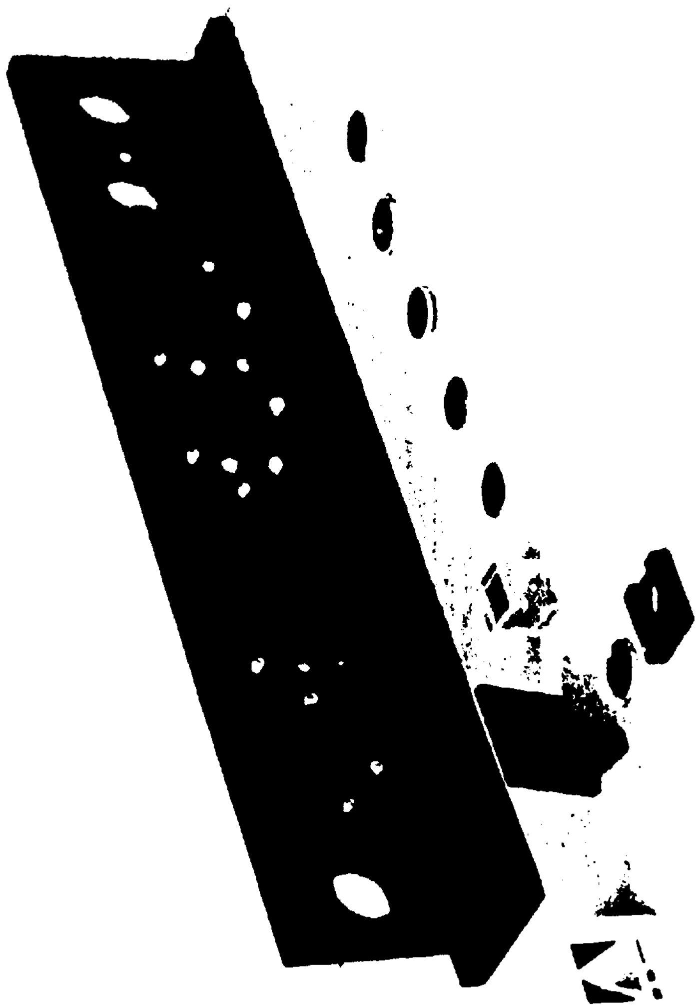
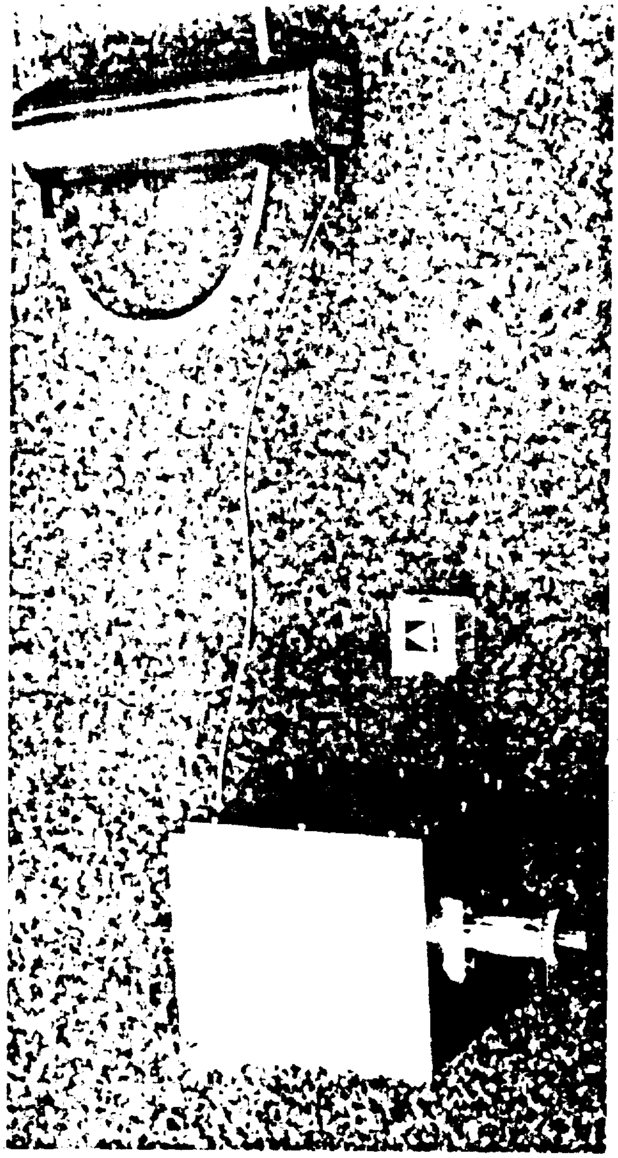
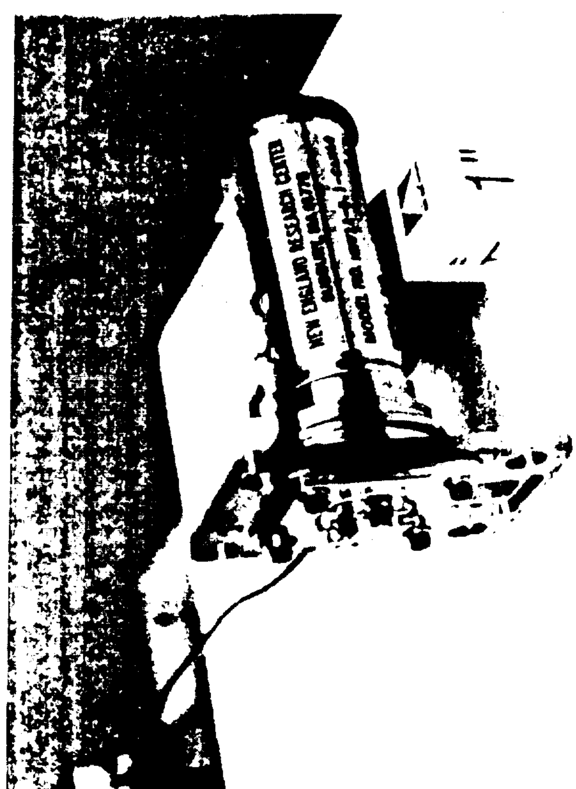
Industrial Products Division

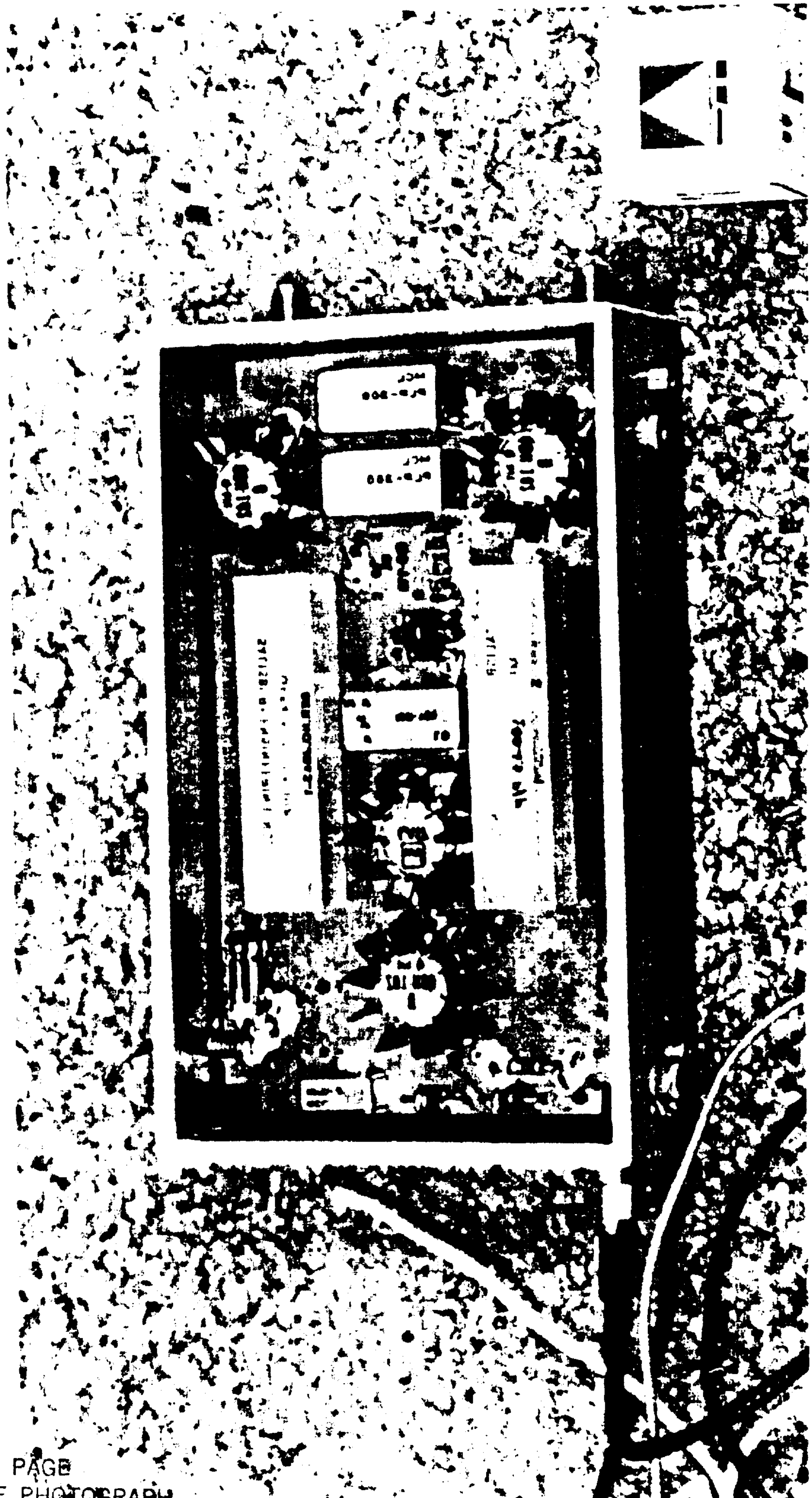


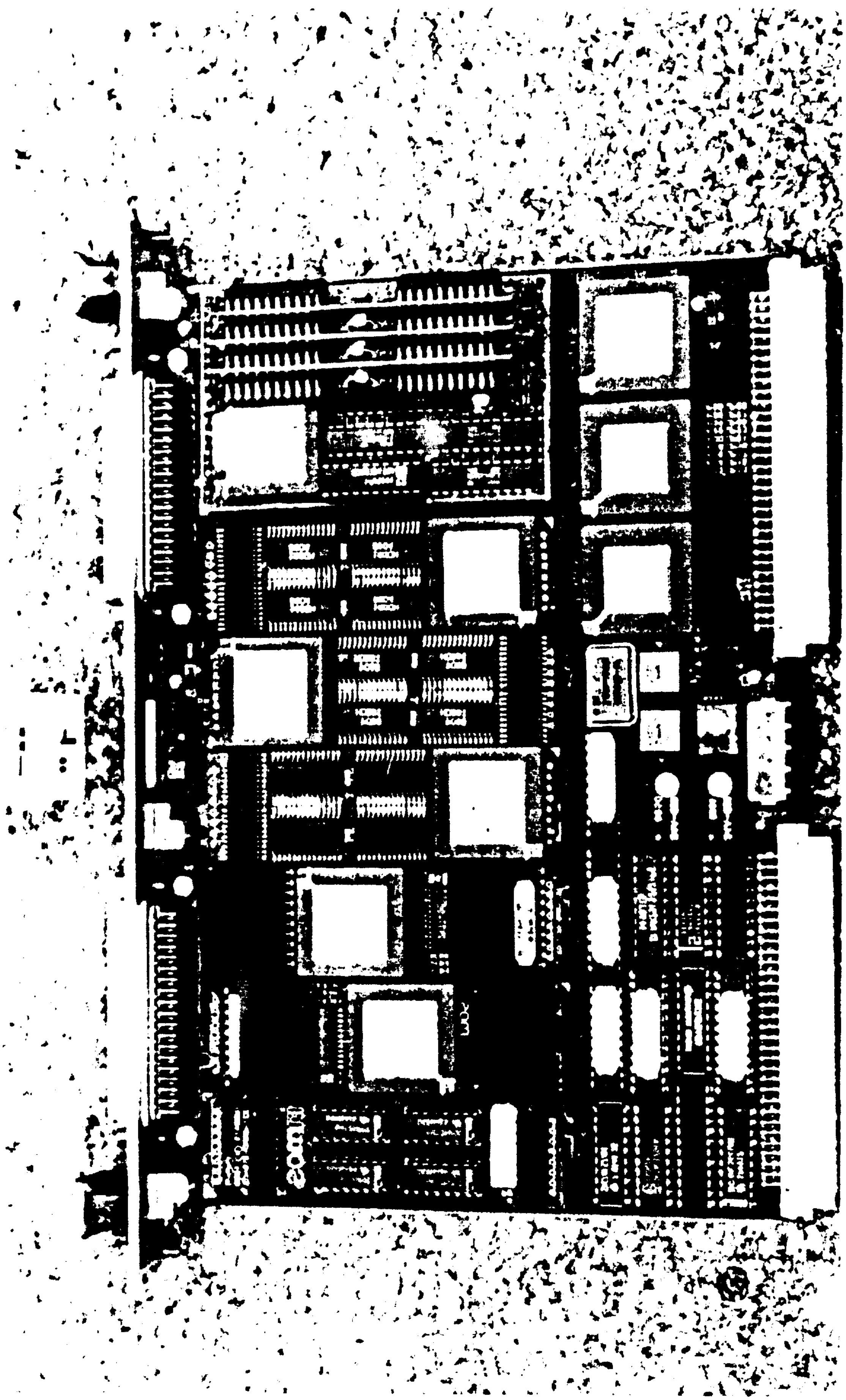












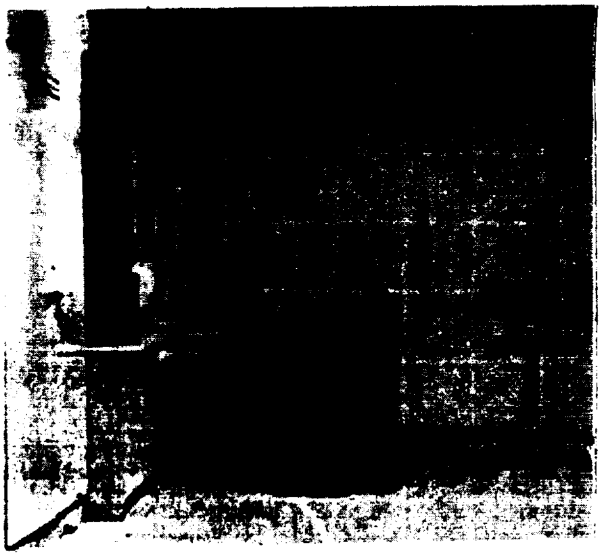
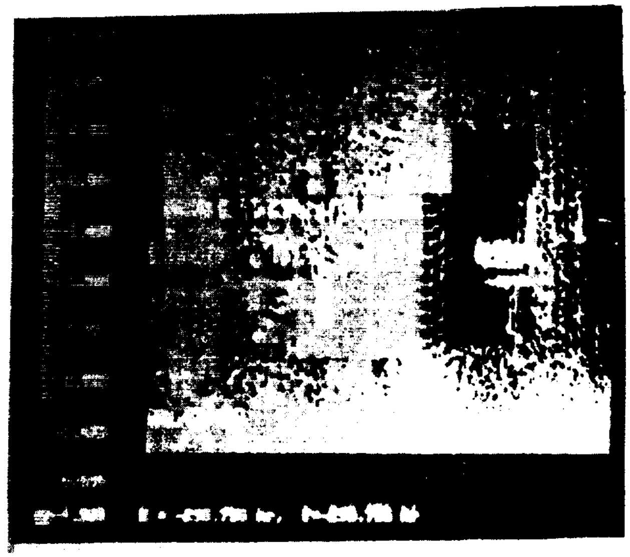
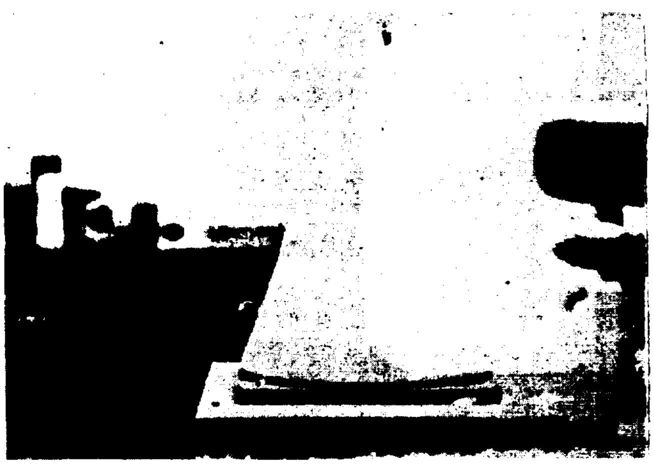


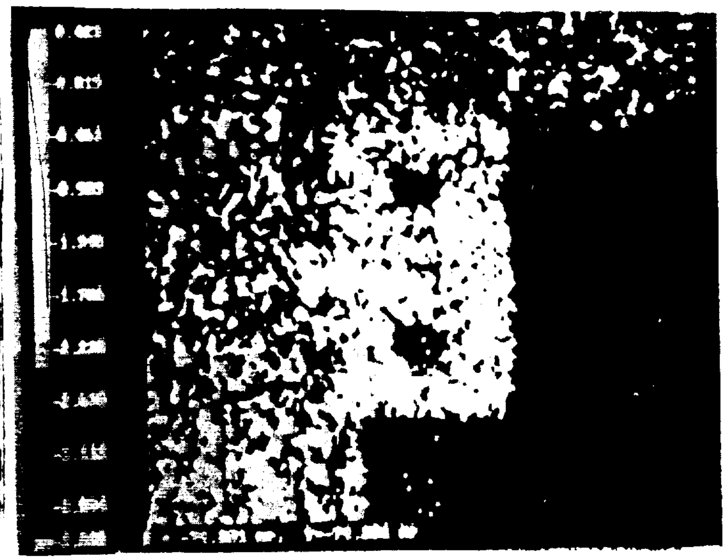
PHOTO OF SCENE 2



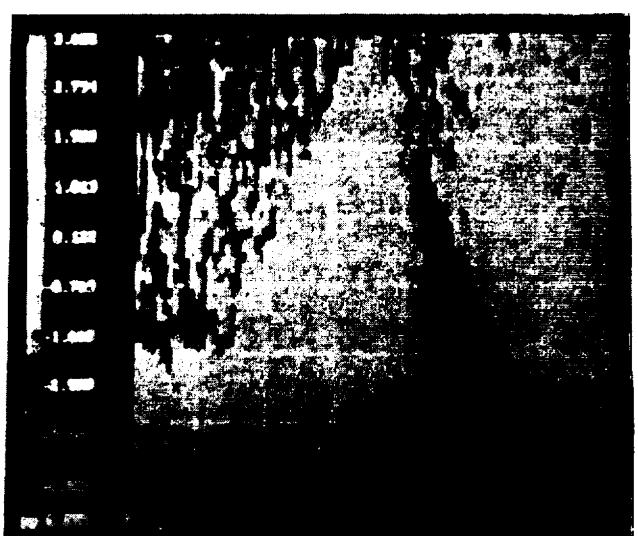
WFOV SCENE 2 (INTENSITY)



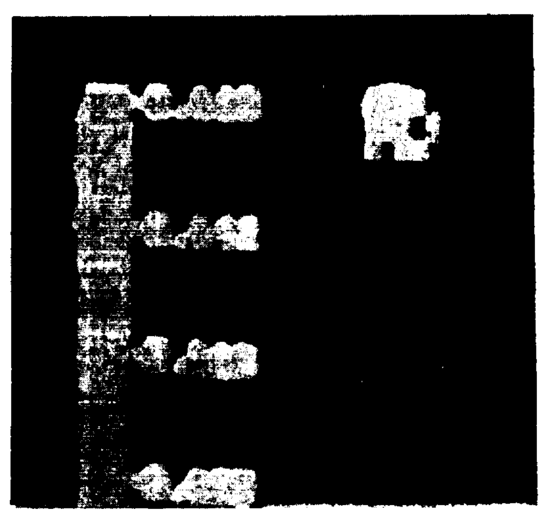
ROTATIONAL DOPPLER TARGET



FOVEAL SCAN OF FOAM BLOCK (INT)



NFOV DOPPLER IMAGE

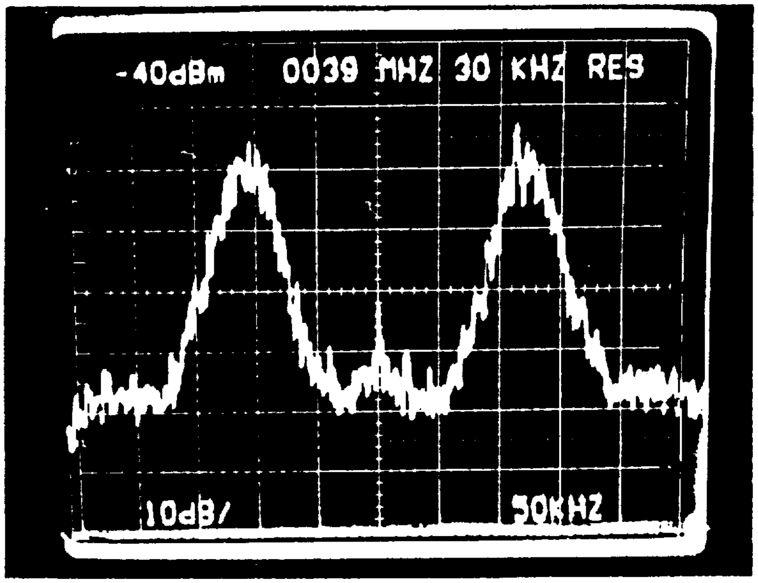


SIMULATED CORNER TRACK
OF FOAM BLOCK (INTENSITY)

6.4 Supporting Data

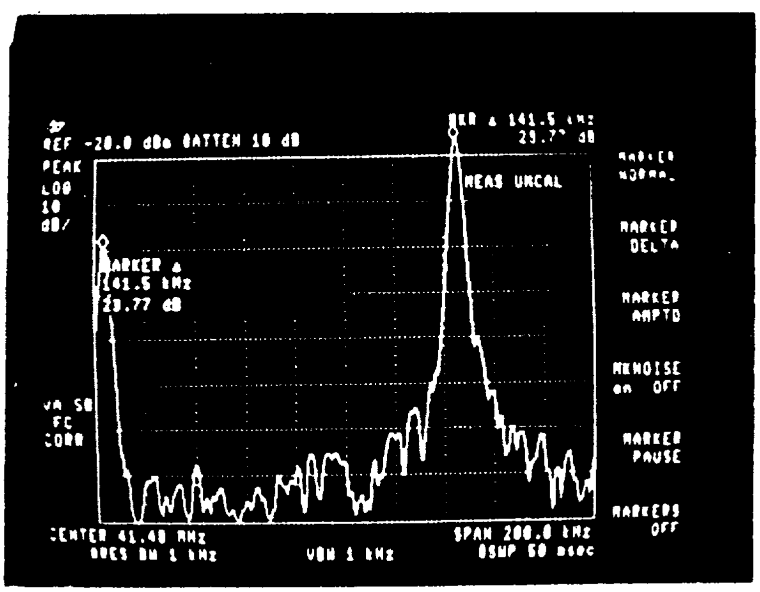
6.4.1 Doppler Measurements

Rotating Diffuse Cone at 30°



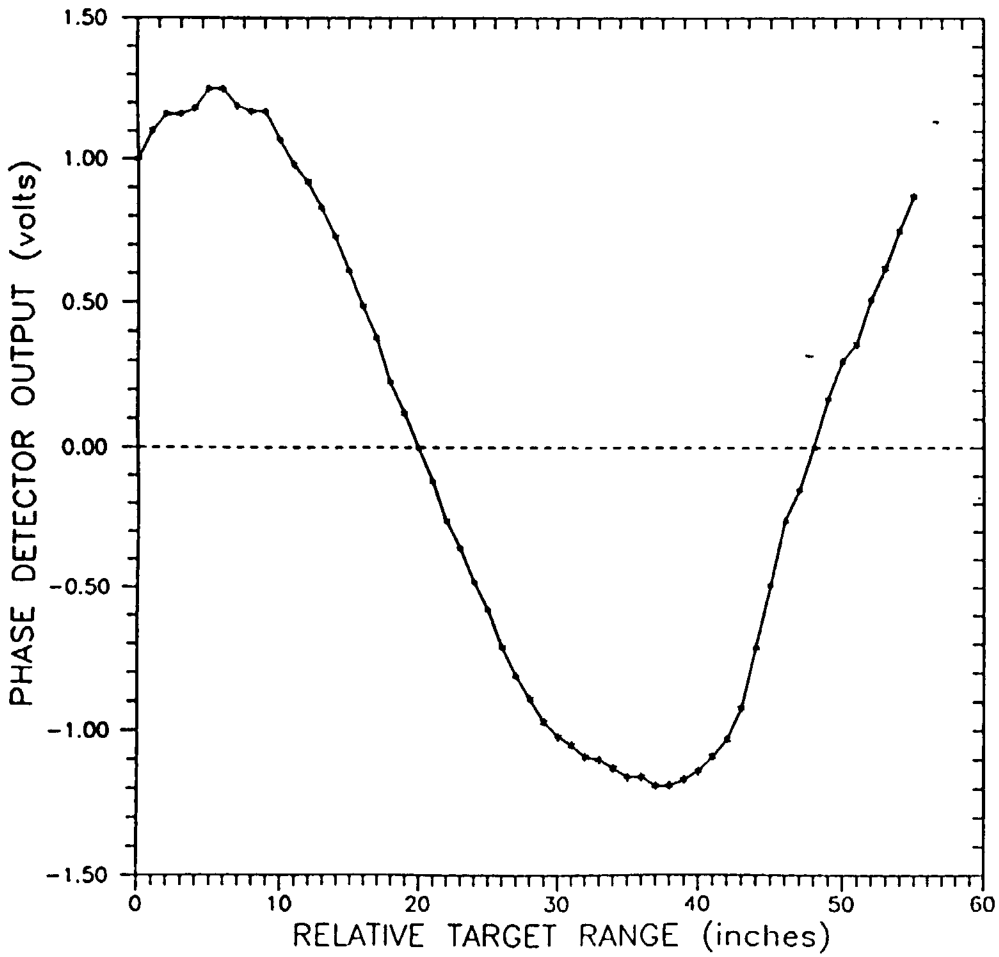
8/88 No offset optical modulator, electronically shifted to 40 MHz. Doppler causes baseband foldover CNR = 40 dB in 30 kHz

Translating Retro-Reflector at 20°



2/89 Detector pre-amp output. Single 40 MHz offset modulator.
Doppler shift = 141.5 kHz
Velocity = 749.5 mm/s
CNR = 80 dB in 1 kHz

$\sigma_{\Delta V} = .3$ mm/s



PHASE I ADAPTIVE GRASPING
AM–CW RANGE PROCESSOR
TRANSFER FUNCTION SHOWING
30 INCH UNAMBIGUOUS
RANGE MEASUREMENT
RETURN FROM 1 INCH
RETROREFLECTOR

σ = .5mm

AUTONOMOUS RENDEZVOUS AND DOCKING SYSTEM DESIGN AND SIMULATIONS

PRESENTED TO

AUTONOMOUS RENDEZVOUS AND DOCKING CONFERENCE

JOHNSON SPACE FLIGHT CNETER

AUGUST 15-16, 1990

PREPARED BY

Richard W. Dabney

NASA-Marshall Space Flight Center

AUTONOMOUS RENDEZVOUS & DOCKING SIMULATIONS AT MSFC

MSFC DYNAMIC MOTION SIMULATION FACILITY

- O OVERHEAD CRANE (8 DEGREES OF FREEDOM)
- O AIR-BEARING VEHICLE WITH GIMBAL SYSTEM (6 DEGREES OF FREEDOM)
- O CAPABILITIES: RANGE UP TO 120 FEET
  NO ATTITUDE RESTRICTIONS
  NO SIGNIFICANT RATE RESTRICTIONS

RECENT AR&D SIMULATIONS:

- TWO-POINT DOCKING OF MOBILITY BASE WITH PLATFORM
  - o CCD SENSOR
  - o PHASE PLANE CONTROL ALGORITHM
- THREE-POINT DOCKING OF OVERHEAD CRANE WITH REALISTIC HUBBLE SPACE TELESCOPE MOCKUP
  - o IMPROVED CCD SENSOR
  - o TRW OMV-BASED CONTROL ALGORITHMS

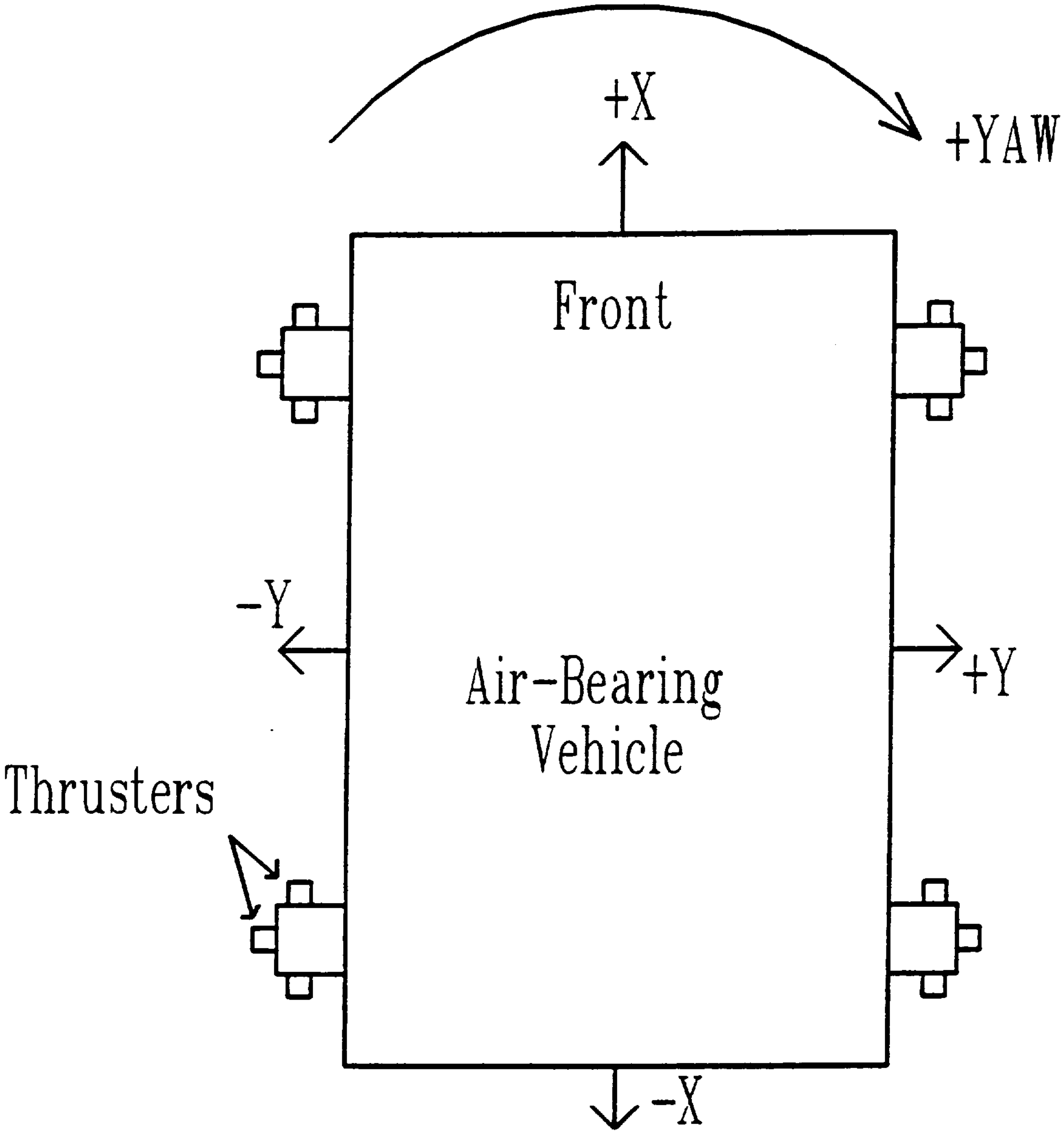


Figure 1 - Mobility Base

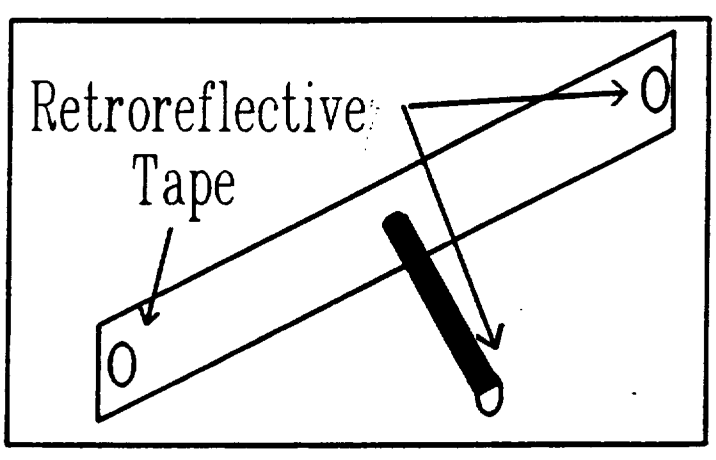
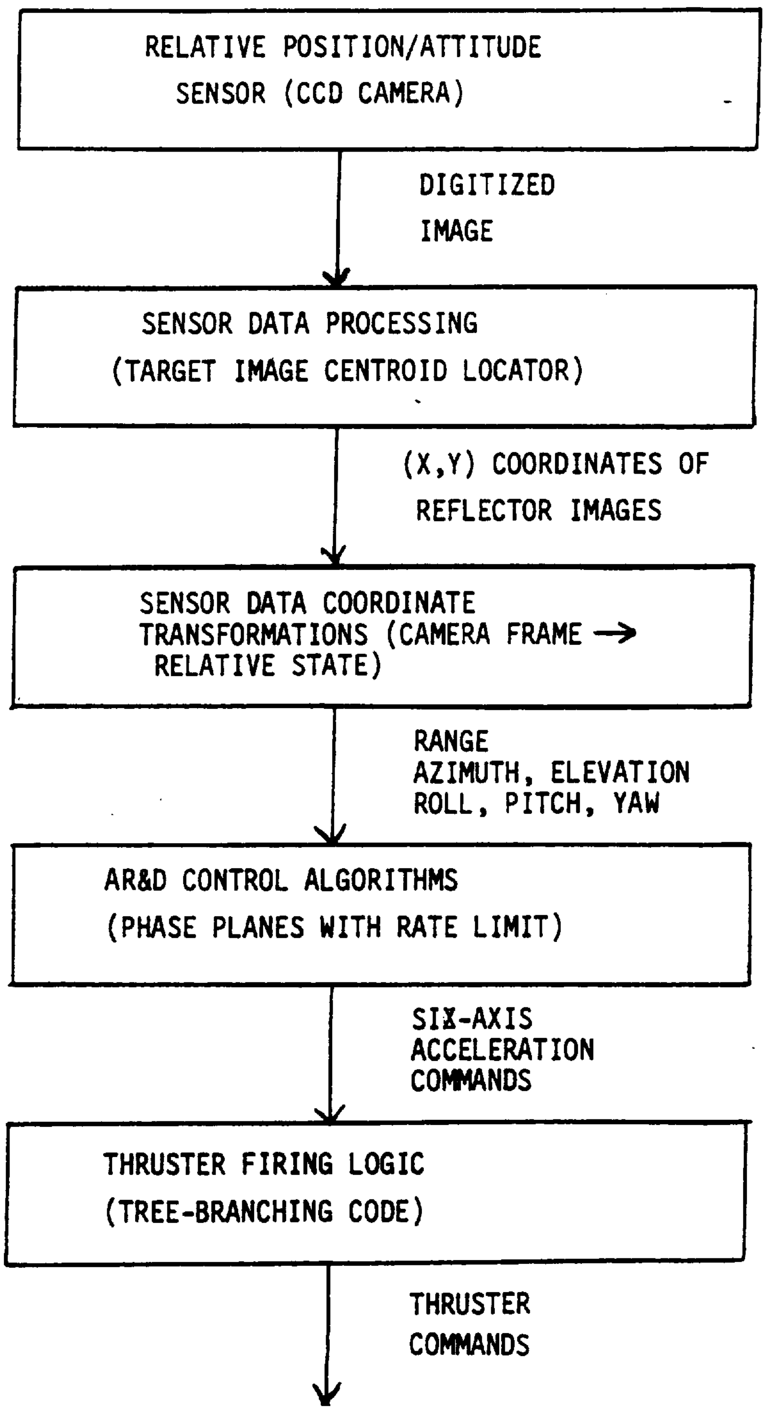


Figure 2 - Docking Target

MSFC AR&D SYSTEM BLOCK

DIAGRAM



Program Flow

Target Azimuth, Elevation,
Sensor Azimuth, Elevation,
Relative Range, Roll

Filter Sensor Data to
Reduce Noise
$\theta_i(t) = .5*(\theta_i(t)+\theta_i(t-dt)$

Derive Rates
$w_i(t)=(1/2dt)*(\theta_i(t)-\theta_i(t-dt))$
$+ .5*w_i(t-dt)$

Compute Error Signals
$e_i = (\theta_i a_i + w_i b_i) * 6.0$

Upper and Lower Error
Command Limits
if $(e_i > 6)$ then $e_i = 6$
if $(e_i < 2)$ then $e_i = 2$

Upper and Lower Rate Limits
if $|w_i| >$ rate limit then
$e_i = \cdot 3$

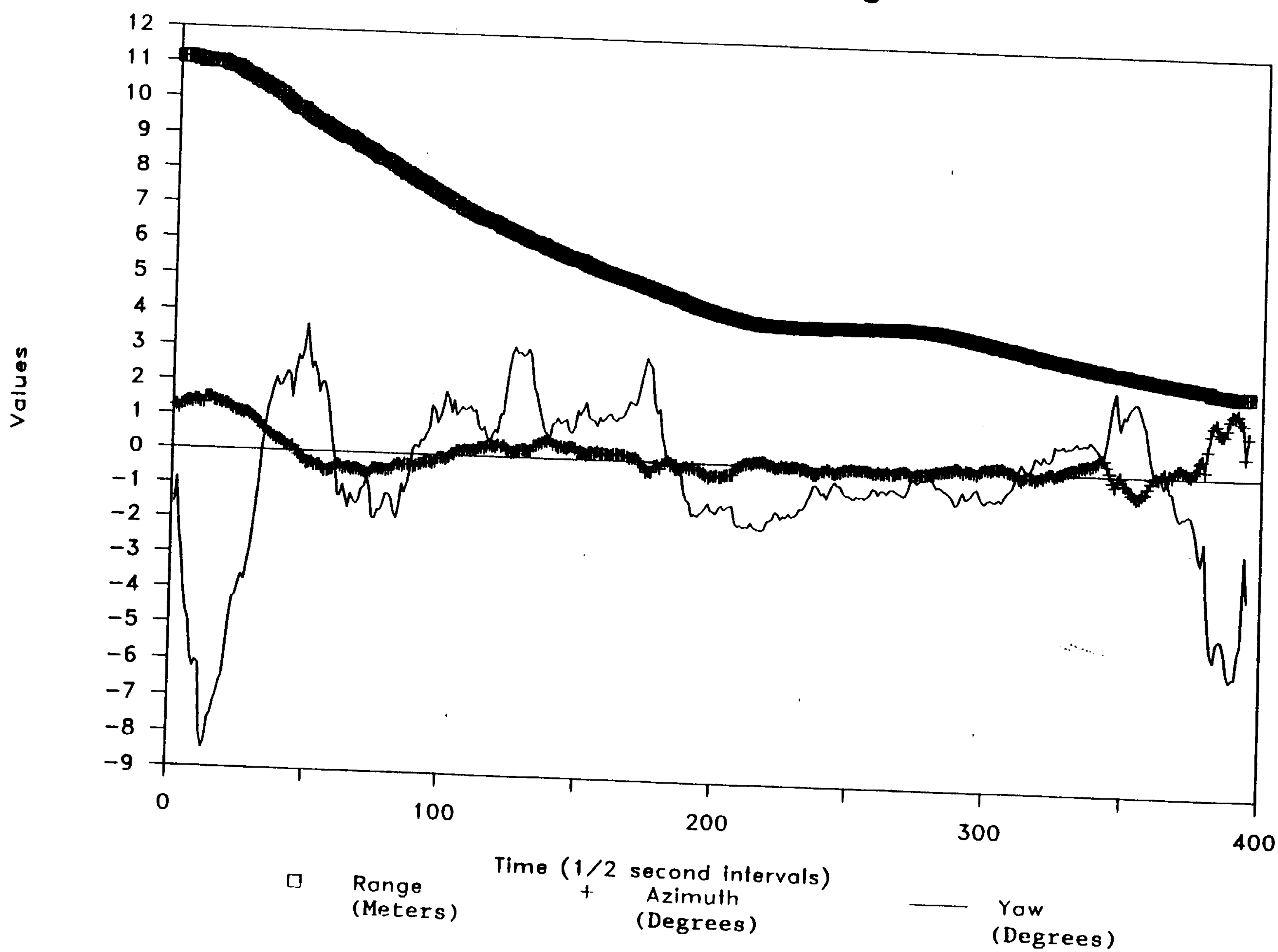
Vehicle Commands to Thruster
Selection Logic
(Through serial port)

Gains and Rate Limits

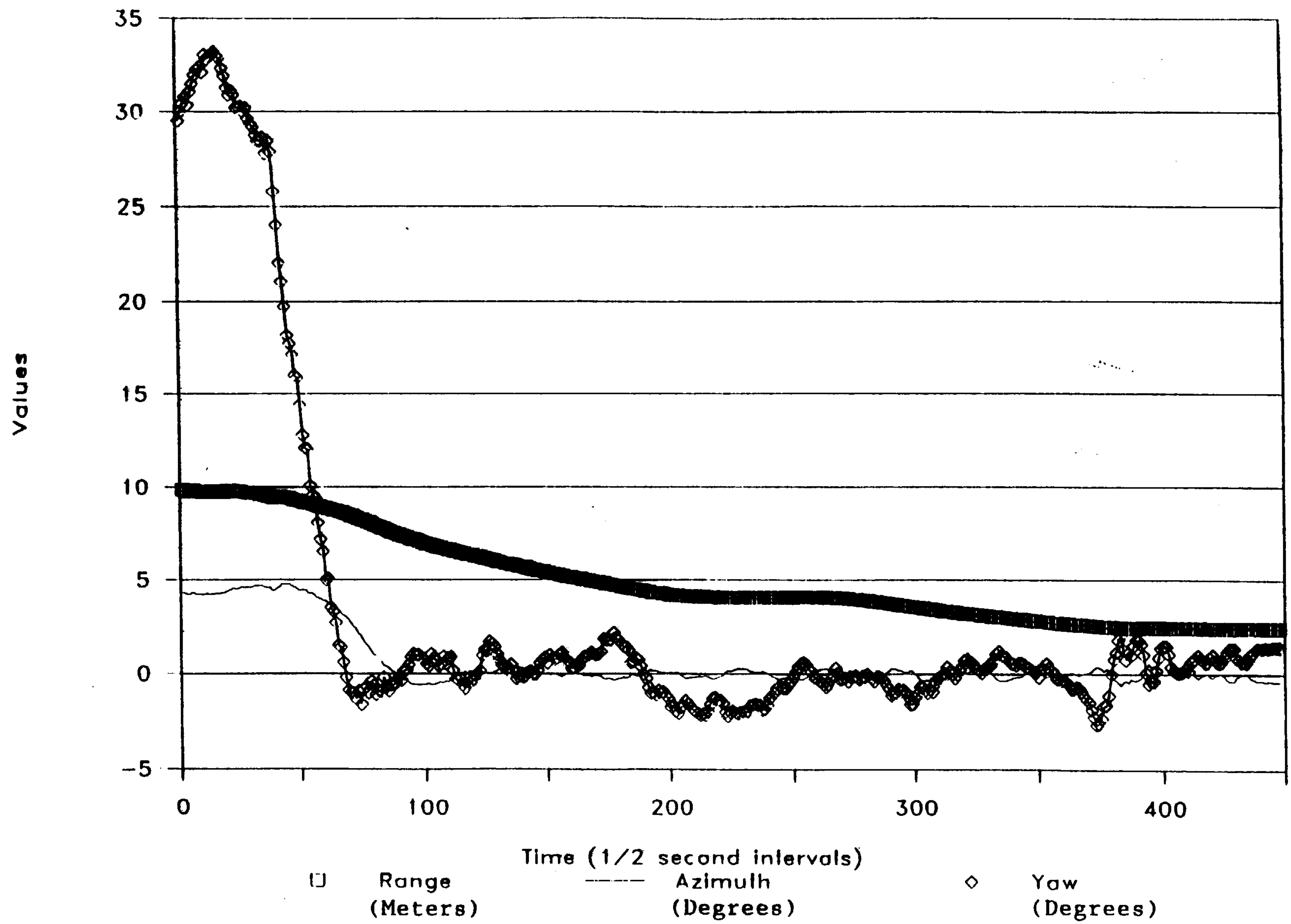
Input Signal	Position Gain	Rate Gain	Rate Limit	Output Signal
θ_0 Range	.25	10	*	e_0 (X)
θ_1 Sensor Azimuth	.5	5	1.4	e_1 (Y)
θ_2 Target Azimuth	.1	.5	1.0	e_2 (Yaw)
θ_3 Sensor Elevation	.18	1	2.8	e_3 (Z)
θ_4 Target Elevation	.1	.1	1.0	e_4 (Pitch)
θ_5 Roll	.15	.1	2.8	e_5 (Roll)

* Rate Limit = range/120 + .01

Automatic Docking



Automatic Docking



NEURAL NETWORK APPLICATIONS IN AR&D AT MSFC

- POTENTIAL APPLICATIONS
  - SENSOR DATA PRE-PROCESSING
  - NONLINEAR TRANSFORMATIONS/INVERSE FUNCTION IMPLEMENTATION
  - ADAPTIVE CONTROL ALGORITHMS
  - SYSTEM HEALTH MONITORING/REDUNDANCY MANAGEMENT

- GENERAL ADVANTAGES
  - TAKE BETTER ADVANTAGE OF PARALLEL PROCESSING HARDWARE
  - ANALOG AND DIGITAL IMPLEMENTATIONS POSSIBLE
  - CAN ACCOMMODATE REAL-WORLD EFFECTS WHICH ARE DIFFICULT TO MODEL ANALYTICALLY
  - CAN ADAPT TO UNEXPECTED CHANGES IN SYSTEM PERFORMANCE
  - IDEAL FOR SYSTEMS EMPLOYING MULTIPLE SENSORS

NEURAL NETWORK APPLICATIONS IN AR&D AT MSFC

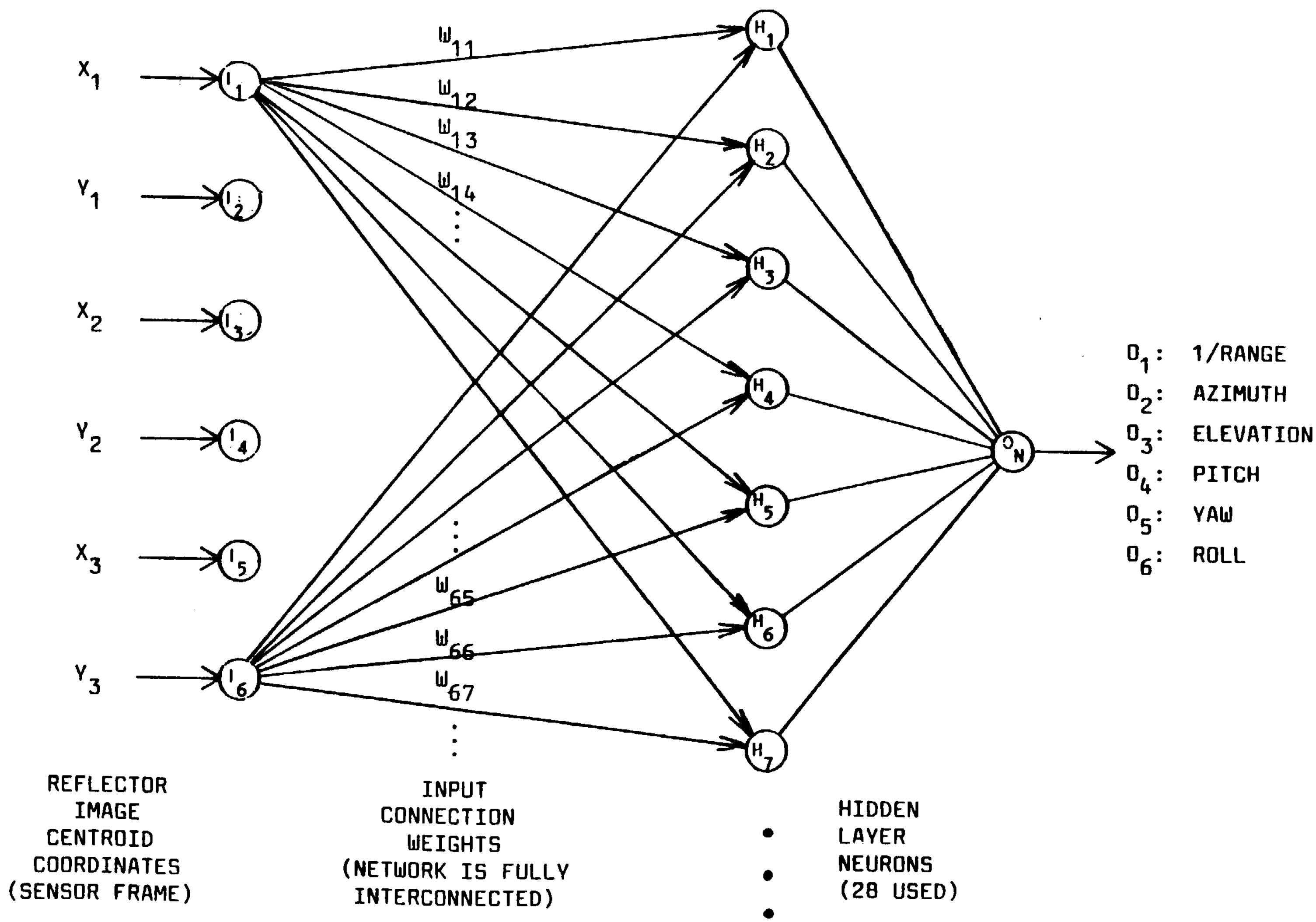
- CURRENT SPECIFIC RESEARCH OBJECTIVE: DEVELOPMENT OF NEURAL NETWORKS FOR DERIVATION OF RELATIVE ATTITUDE AND POSITION DATA IN VEHICLE FRAME FROM DOCKING TARGET REFLECTOR CENTROID COORDINATES IN SENSOR FRAME

<u>APPROACH</u>:

- A SEPARATE NETWORK IS USED FOR EACH RELATIVE STATE DEGREE OF FREEDOM
- NETWORKS FOR RANGE, AZIMUTH, AND ELEVATION RECEIVE ACTUAL REFLECTOR POSITIONS IN CAMERA FRAME AS INPUT
- NETWORKS FOR TARGET ROLL, PITCH, AND YAW RECEIVE NORMALIZED AND CENTERED REFLECTOR POSITION COORDINATES AS INPUT (THIS WAS EXPERIMENTALLY FOUND TO INCREASE ACCURACY AND REDUCE TRAINING TIME)
- ALL NETWORKS ARE THREE-LAYER, FEED-FORWARD NETWORKS WITH 28 HIDDEN NEURONS
- RANGE NETWORK IS TRAINED TO COMPUTE RECIPROCAL OF RANGE, WHICH DECREASES TRAINING TIME
- ALL NEURONS HAVE SIGMOID TRANSFER FUNCTIONS
- ALL NETWORKS ARE TRAINED USING BACK-PROPAGATION ALGORITHM

NEURAL NETWORK APPLICATIONS IN AR&D AT MSFC

BACK-PROPAGATION NEURAL NETWORK ARCHITECTURE



NEURAL NETWORK APPLICATIONS IN AR&D AT MSFC

- RESULTS SO FAR
  - ALL SIX NETWORKS CONVERGE WITH REALISTIC TRAINING SET ENVELOPES
    - o RANGE: 100 FEET TO 3 FEET
    - o AZIMUTH/ELEVATION: $\pm$ 45 DEGREES
    - o ROLL/PITCH/YAW: $\pm$ 45 DEGREES
- ALL SIX NETWORKS PROVIDE ADEQUATE TRANSFORMATION ACCURACY
  - o 98% OF TEST POINTS ACHIEVE <10% DEVIATION
  - o 95% OF TEST POINTS ACHIEVE <7% DEVIATION
  - o 80% OF TEST POINTS ACHIEVE <5% DEVIATION
  - o LARGEST DEVIATIONS OCCUR AT OUTER EDGES OF OPERATING ENVELOPE; NEGLIGIBLE DEVIATIONS AT CLOSE RANGE
- PERFORMANCE SUFFICIENT FOR CLOSED-LOOP DOCKING APPLICATIONS

DABNEY/MSFC

AUGUST 1990

NEURAL NETWORK APPLICATIONS AT MSFC

- PLANNED FUTURE ACTIVITIES

  - SIMULTANEOUS USE OF MULTIPLE SENSORS
  - EXPANSION OF OPERATING ENVELOPE
    - MORE TRAINING POINTS
    - IMPROVED TRAINING ALGORITHMS
  - DEVELOPMENT OF NETWORKS FOR ADDITIONAL SYSTEM ELEMENTS
    - SENSOR DATA PROCESSING (PATTERN RECOGNITION, ETC.)
    - CONTROL LAWS
    - THRUSTER FIRING LOGIC
  - COMPLETE DYNAMIC COMPUTER SIMULATION OF AR&D WITH EXTENSIVE USE OF NEURAL NETS
  - HARDWARE-IN-THE-LOOP DEMONSTRATION OF NEURAL-NET AR&D AT THE MSFC DYNAMIC MOTION SIMULATION FACILITY

C-3

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